

BBC
RADIO



The Infinite
Monkey Cage

THE SUNDAY TIMES BESTSELLER

HOW TO BUILD A UNIVERSE

(PART 1)

PROFESSOR

BRIAN
COX

ROBIN
INCE

& ALEXANDRA FEACHEM



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PART 1



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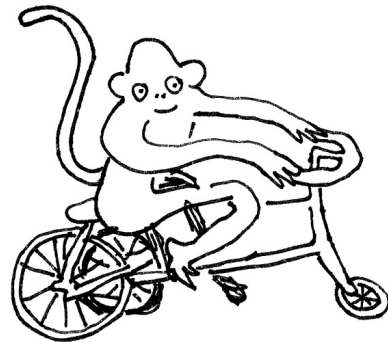
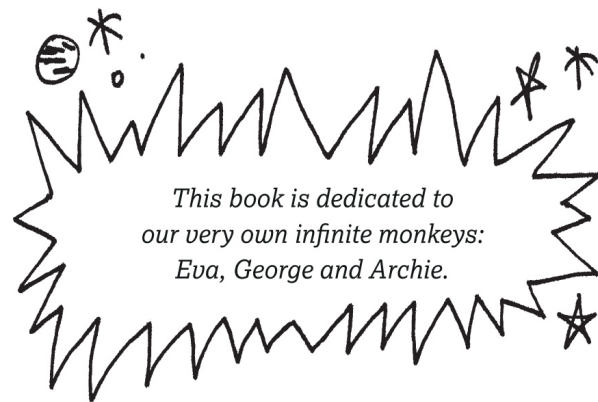
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‘A joyous trip through our understanding of the universe’

Daily Express Praise for BBC Radio 4’s The Infinite Monkey Cage: ‘A witty and irreverent look at the world according to science’

Independent

Praise for Professor Brian Cox: 'Engaging, ambitious and creative'

Guardian

‘He bridges the gap between our childish sense of wonder and a rather more professional grasp of the scale of things’

Independent

‘Professor Cox shows us the cosmos as we have never seen it before – a place full of the most bizarre and powerful natural phenomena’

Sunday Express Praise for Robin Ince: ‘Bursting with energy and ideas’

The Times

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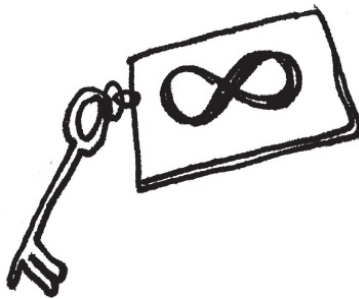
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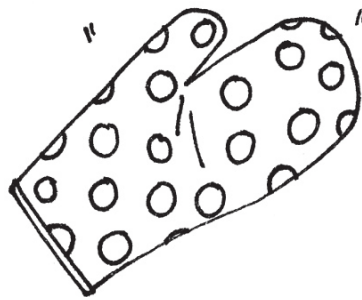
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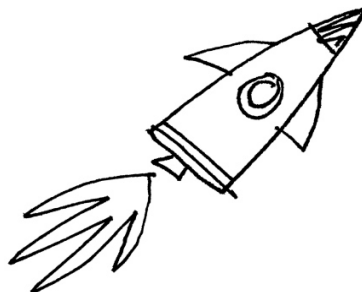
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Recipe to Build a Universe



Space Exploration



Evidence & Why Ghosts Don't Exist



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A BEGINNING

A Very Special Foreword by *Eric Idle* Hello.

Sorry to come barging into this pseudo-scientific book, but obviously publishers are greedy bastards and will do anything they can to try to seduce the gullible public into buying enormous quantities of meretricious trash for the Christmas market, so I have been asked to lend my name to this blatant attempt to part you from your cash.

What is *The Infinite Monkey Cage* anyway – apart from being a terrific song written and sung by yours truly with every single instrument played by Jeff Lynne, and certainly something you should try to download for Christmas, but no, it's the sodding BBC and it's not available or they'd have to pay for something. That's why you are stuck with this book.

I think you will find it very helpful. It's useful for keeping a door propped open or to put on your Christmas table to stop the hot plates blistering the plastic tablecloth. But do watch out for the Christmas pud; the book itself is highly flammable, and if it catches, you might possibly set fire to an elderly aunt. On the other hand, if you are cold, simply stick it in the grate and it will make a lovely Christmas blaze.

As you know, scientists are the new chefs, so pity poor Ince, once a half-way decent comedian, now stuck alongside a glamour-boy professor, playing Robin to his Batman. Still, if it stops him having to play Colchester again I suppose the whole thing has been worth it.



One or two words about *The Monkey Cage* itself.
Is the *Cage* infinite?
Or are the *Monkeys* infinite?
Or perhaps they are *both* infinite?
In a multiverse would there be an Infinite *Donkey Cage*?
I think we should be told.

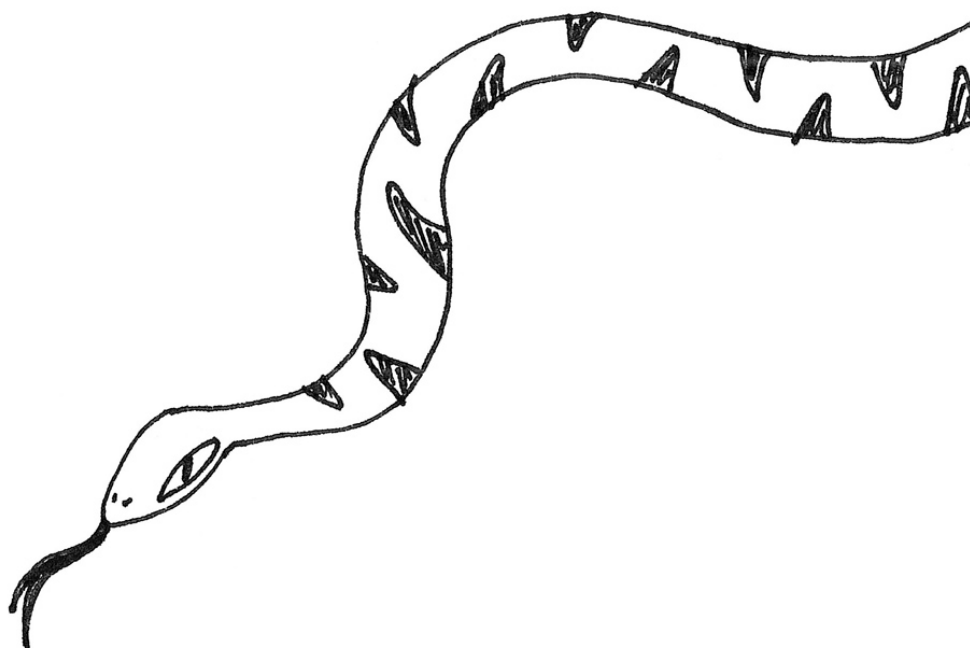
Well, that's about it.

I shall be spending my Christmas Day in the traditional way on a Thai massage table listening to *Sounds of the Seventies*. Sadly, we don't get the Queen's speech here in Bangkok, but there are one or two compensations. There is an inspirational message from José Mourinho, and a bottle of gluten-free almond wine for ancient tee-totalling ex-Pythons sent by John Cleese from his cellars, where he hangs upside down during the winter season.

To all of you, please enjoy your expanding Universe for another year. And do try to buy more Monty Python shit. We haven't got long and we do need the cash.

Happy Christmas Greetings!

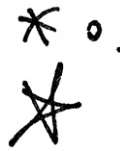
Eric Idle
The Old Jokes Home Thailand





A WORD FROM THE PRODUCER

The Producer's Tale *by Alexandra (Sasha) Feachem*



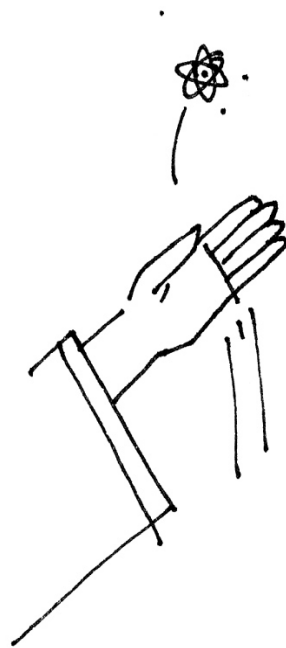
Hello, I'm Sasha. I produce the radio show *The Infinite Monkey Cage*. I say produce, I use the term loosely. You'll understand why in a moment. Brian thought it would be a good idea if I wrote something about what it is like to work with him and Robin. I'm not sure he had fully thought through that suggestion when he made it. I responded with hysterical enthusiasm. Brian looked scared. Perhaps punching the air and shouting 'Yes! Finally the world will hear my story' was a nanometre over the top.¹ Despite this, and trying desperately to hide his alarmed expression behind a nervous smile, Brian realised that retracting the suggestion was clearly not an option... that the horse, or monkey keeper, had well and truly left the infinite zoo enclosure at something approaching the speed of light.

So here I am, with the producer's tale; to tell you how *The Infinite Monkey Cage* evolved into existence and what it's like to work with the infinite monkeys. And although the title of the show was in no way chosen to reflect the personalities of the people involved, or the way the radio show is put together, there is no doubt that we have all gloriously grown into the title. Thank goodness we didn't call it *Top Geek*.

Back in 2008, CERN switched on the mother of all science experiments: the Large Hadron Collider. It is still the longest, fastest, most expensive science experiment ever undertaken. A particle smasher of biblical proportions, it recreates the moment just a billionth of a second after the Big Bang, and is the ultimate testament to what happens when human beings get together and ask why and what if? And when the Large Hadron

Collider did switch on, Brian and I were sitting in the control room at CERN, alongside Andrew Marr, broadcasting to the nation, live on the *Today* programme. It was quite an odd experiment in itself, doing live coverage of a science experiment that is hidden underground and involves minuscule particles that I think even David Attenborough would fail to do justice to, especially on the radio. As Evan Davis commented from the safety of the *Today* studio back in London, ‘it’s a bit like Olympic taekwondo. It all sounds very interesting, but no one is quite sure what is actually going on.’

Luckily, the much predicted black hole that had gripped the popular press did not materialise and we all lived to tell the tale.² And of course just a few years later, this extraordinary machine discovered the elusive Higgs particle, and with it gave us the origin of mass and opened a whole new chapter in our quest to understand the Universe we live in.



But perhaps the most extraordinary achievement of this jaw-dropping experiment was the interest it ignited in the general public; suddenly, incredibly, science was cool. Not just science, but particle physics. Some very well-known voices and faces emerged from the shadows and declared themselves fans of physics. Science had become, dare I say it, a little bit rock ‘n’ roll, and so the idea for *The Infinite Monkey Cage* was born.

Brian had told me some hilarious tales about celebrities he'd encountered on his travels, from dinners with Dan Aykroyd to finding himself in a hotel suite with Cameron Diaz and Queen Noor of Jordan... all fans of particle physics, not just Brian's hair. One of Brian's friends told us that we should try to get hold of Mick Jagger (he's 'way up on this shit', apparently!). What could be more rock 'n' roll than that? (Mick – if you're reading this, we'd still love to hear from you.) Robin, at this point, was regularly performing and curating his hugely popular stand-up shows, mixing scientists with comedians, and so this odd idea of a Radio 4 panel show featuring scientists and celebrities was born. Robin came up with the title and now, nearly 10 years later, it doesn't seem like such an odd idea to have comedian Katy Brand on stage with Professor Carlos Frenk, one of the world's most esteemed cosmologists. Or Ross Noble sitting alongside an expert in early human fossils. Or even a Python (Monty) and a geologist.





But I think the moment when I seriously began to believe in the possibility of parallel universes was the first time we took to the stage at Glastonbury, in 2011, to be greeted by the deafening cheers of more than 3000 people. These rock-festival goers, most of them still probably the worse for wear from the night before, had stampeded across fields of mud to cram into the cabaret tent at the most famous music festival in the country to see a comedian and a physicist take to the stage to talk about rationality, evidence and the wonders of science.

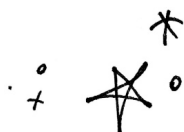
‘Who’s here for particle physics?’ shouted Robin. The 3000 people screamed back. ‘Quantum Chromodynamics?’ shouted Brian, to even more enthusiastic cheers. ‘It’s not very Radio 4 is it...?’ observed Brian. Not very Radio 4, and not, some might argue, very sciencey. But why shouldn’t it be?

One of the most frequent complaints we get to the radio programme (usually, I have to say, from people who have never listened), is that we are dumbing down science. Have you heard one of Brian and Robin’s introductions?! I’m sorry, but ‘yo mamma’s so massive she’s redshifted’ has got to be one of the most highbrow jokes ever heard on Radio 4. You need a PhD in astronomy to really keel over laughing at that one. The rest of us just sit and look a bit baffled, although we very much enjoy watching Brian giggling away and we feel happy that we know the joke might be funny once we’ve had a chance to go home and do some homework.³

To accuse the show of dumbing down science is to fundamentally misunderstand its purpose and the real reason why we all feel so passionately about its central message. Science is arguably the single biggest force in culture today. Cloning, genetic modification, nuclear power, the web, modern medicine – you name it, science is changing our world. Turn your back on science and you turn your back on the future and you fail to understand the present. To be truly engaged in society, everyone needs a basic grasp of what science is about and the way of thinking that leads to the advances that we all take for granted.

Science is vitally important, and therefore it must be part of popular culture. Why would anyone want to leave the foundation of our society to the boffins? They are just people, after all – they laugh, they cry, they watch *Love Island* like the rest of us.⁴ And comedians and entertainers read books, and newspapers, use hospitals and drive cars, and take an interest in the world around them, and in some cases had whole careers in quantum physics or cosmology before being lured away by the thrill of treading the boards (hello, Ben and Dara).

What I love most about working on the show is that in mixing these amazing people together, and putting a comedian and a physicist in charge, you never quite know what you are going to get. It's chaotic and anarchic and a little bit terrifying if you are the producer, and possibly if you are the listener, too, but whatever the outcome, it is always interesting and surprising, and most of all we hope it makes people think. Brian and Robin really are the infinite monkeys, and although we may set out hoping to produce the works of Shakespeare, what emerges at the end, just like the theory we are named after, is a splendid testament to randomness. But despite the infinite chaos, and the anarchic bamboozlement, I hope we are never dull, and that we do the best job possible at fighting the corner for evidence, rational thinking and the glory and wonder of scientific endeavour and asking questions. After all, science allows you to write the secrets of the Universe on a blackboard, and what's not to love about that?

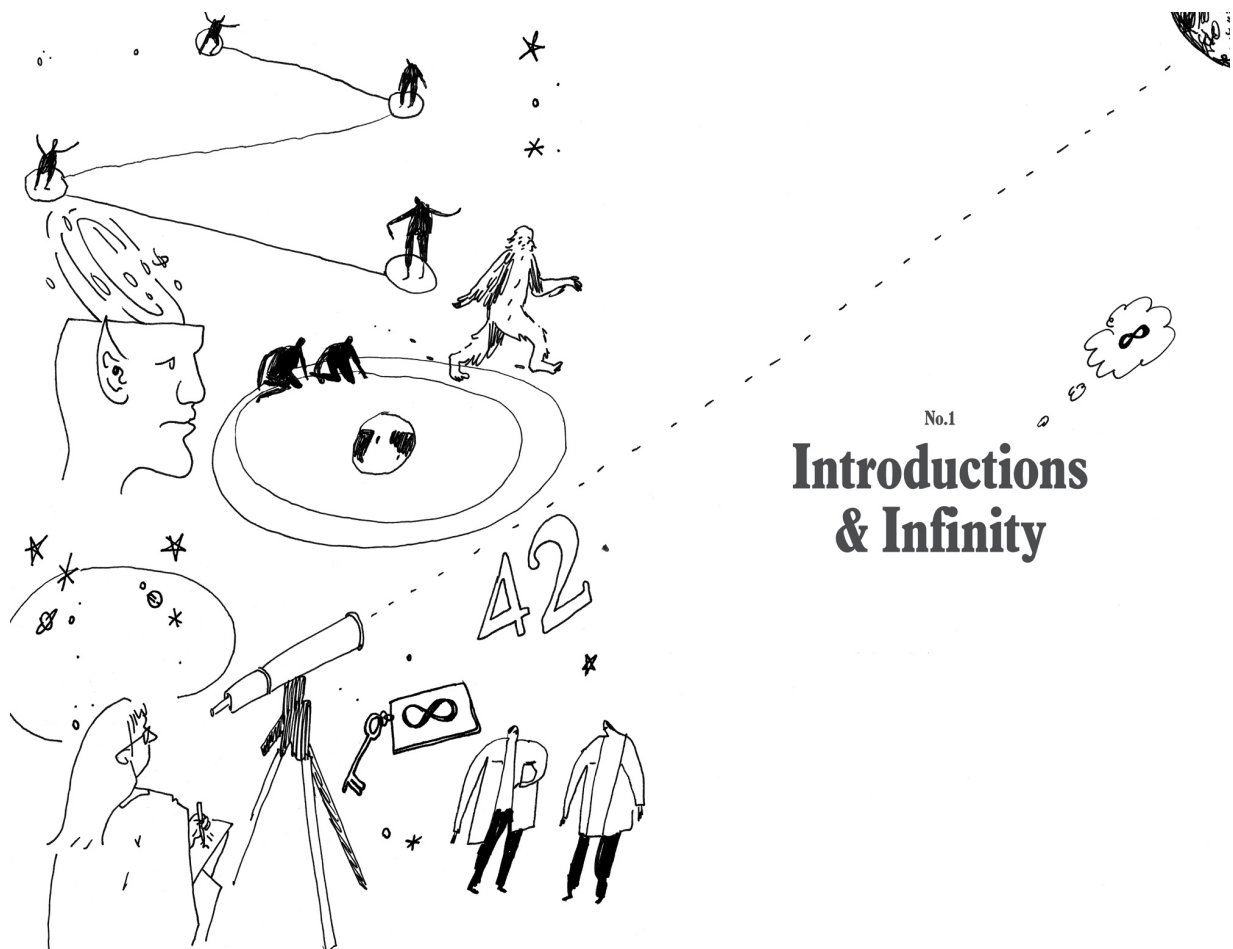


¹ Brian: A nanometre is 10^{-9} metres – that's one-billionth of a metre. This sentence implies that Sasha went around 10 helium-atom-diameters over the line of acceptable excitement.

² Brian: By 'popular press', Sasha means the *Daily Mail*, whose headline 'Are we all going to die next Wednesday?' should, if accuracy was the only goal, have led a one-word article: No.

³ Brian: This experience will be familiar to anyone who has been in the audience at one of Robin's stand-up gigs.

⁴ Brian: I don't even have to say it, do I?



AN INTRODUCTION

Welcome to *The Infinite Monkey Cage*

Hello, I am Robin Ince.



And I am Brian Cox.

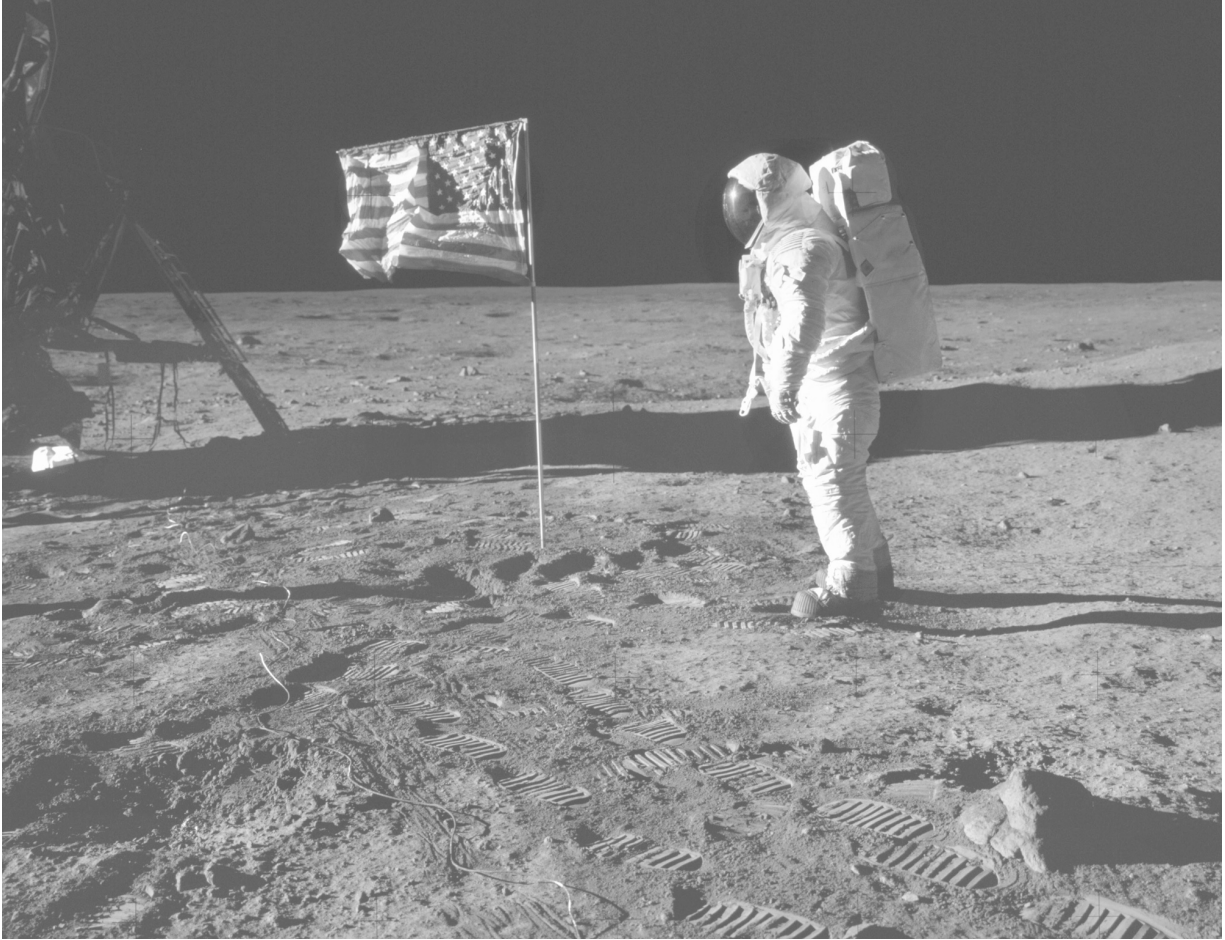




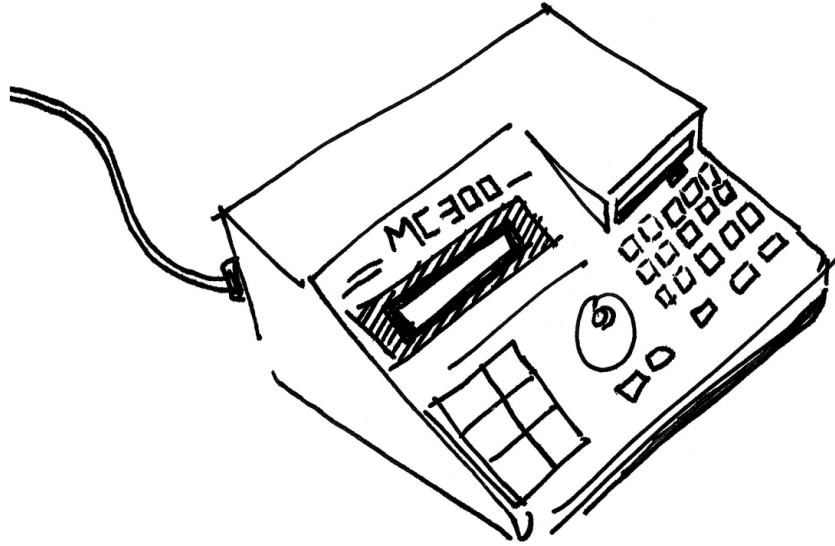
ROBIN: Growing up in the 1970s and 1980s, our interest in space, technology and strange undersea creatures with terrifying tentacles or the ability to eat their own brains came from a mixture of *Look and Learn* magazine, *The Six Million Dollar Man* and *Arthur C. Clarke's Mysterious World*.

BRIAN: We were kids in the Indian summer of the space race, a little too young to remember the Moon landings, but the excitement of exploration still enthused us all. (I myself still own a *Space 1999* outfit.) It was a time of Cold War danger and anxiety, but also of immense optimism and confidence in the promise of science and technology.

R: Sadly, Brian could never become an astronaut because he is too tall and I could never be one because I am too chatty... and short-sighted... and not very patient when it comes to misbehaving machines. So there is no way Apollo 13 would have returned to Earth if I'd been in there gallumphing about and kicking whatever bit of kit that refused to operate as I wanted it to. I am one of those unfortunate humans who believes that objects misbehave with the specific intention of ruining my day. I am likely to be found dead from a heart attack after a blazing row with an inanimate object.



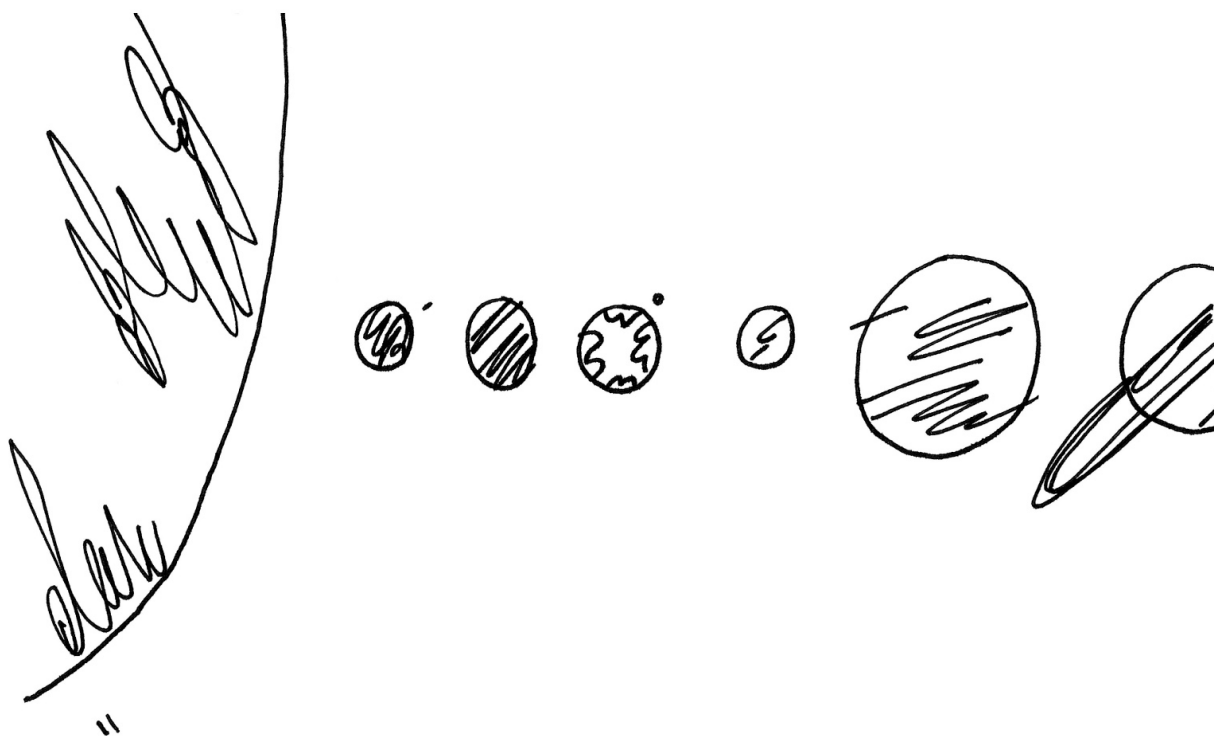
B: Whilst Robin's inability to operate machinery led him to become a comedian, via a degree in one or other of the humanities at some university or other, I became a particle physicist after a short detour via the music industry. Although even then I was primarily interested in programming the Roland MC-300 Micro Composer and only transferred my interest to sex and drugs and rock 'n' roll when my midi cable became frayed.



R: In the early 1980s, television was our teacher. Carl Sagan's *Cosmos* is one of the main reasons why *The Infinite Monkey Cage* exists. Opening with the music of Vangelis, the composer who would also score *Blade Runner* – a film Brian loves as he now knows why he has the same dream about unicorns every night – Sagan's 'spaceship of the imagination' travelled through nebulae and star systems. Music fades, camera pans across a cliff face and zooms into Carl Sagan, and we twelve-year-olds sat up, wide-eyed and eager, and heard the words:

'The Cosmos is all that is, or ever was, or ever will be.'

And thus we were snared. Within minutes, we would know that we were all starstuff, that the stuff of us was the stuff of the stars. The atoms that were currently gathered to form the shape and minds of us had been forged in the furnace of stellar nurseries.



B: Carl Sagan was a pivotal figure for us because he made vivid the link between our science and our humanity. We are a part of the Cosmos, Sagan told us, and our fate is deeply connected with it. Science is devalued when separated from culture, and our experience of living is diluted when we become separated from science, because science is a necessary but not sufficient part of our exploration of what it means to be human. It is not possible to have a meaningful discussion about our place in the Cosmos without knowing its size and scale, without knowing that we are made of it and will return to it, without acknowledging the deep mysteries that await us as we push our understanding ever further back to the beginning of the Universe, 13.8 billion years ago.

Science is often celebrated because it is useful, and research is funded because it provides us with objects of perceived value. The true value of science is that it allows us to acquire reliable knowledge and teaches us humility. Your opinion is irrelevant in the face of nature; imagine the improvement in modern-day political discourse if that single sentence were seared into the forearm of every politician as a cow is branded with the mark of its owner?

Having said that, aircraft, mobile phones, medicine, electric light, refrigerators, vaccines, computers and radios are useful things, and Robin would struggle without the synthetic fibres that strengthen his book-filled rucksack.

We are a part of the Cosmos, Sagan told us, and our fate is deeply connected with it.





Raymond Baxter, the first presenter of *Tomorrow's World*, seen here in 1970 with an innovative doll that can walk, talk and sing.

R: *Tomorrow's World* told us of what was to come, and though often mocked for its adventurous predictions involving round cars on wheeled stilts, much of what was featured on the programme was accurate, intriguing and inspiring. Returning to it now, we are reminded of the speed of change. The unwieldy home computer of 1967 contains far less data-processing capacity than one of the twenty-first century's fancier and, predominantly, pointless, wristwatches.

'Imagine a world where every word ever written, every picture ever painted and every film ever shot could be viewed instantly in your home via an information superhighway, a high-capacity digital communication network... it sounds pretty grand, but in fact this is already happening on something called the internet'

Kate Bellingham told us in 1994.

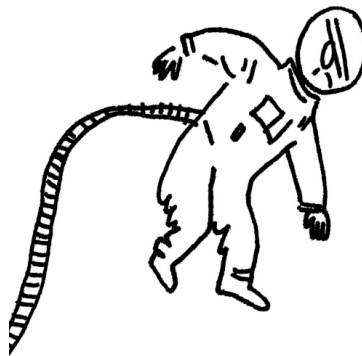
1994!

Imagine a world without something called the internet. Imagine how hard it would be to shop, watch or destabilise democracy and seed disinformation.





William Wollard, former presenter on *Tomorrow's World*, seen strolling up the roof of St Pancras Station in London in 1970, made possible through the cunning invention of Herbert Stokes' 'Roof Shoes'.



B: As children, the divide between science, pseudoscience and plain nonsense was not as marked in our minds as it is now, but perhaps paradoxically the lines were more clearly drawn in public discourse. In his

book *The Demon-Haunted World*, published in 1995, Carl Sagan wrote: ‘I have a foreboding of an America in my children’s or grandchildren’s time – when the United States is a service and information economy; when nearly all the key manufacturing industries have slipped away to other countries; when awesome technological powers are in the hands of a very few, and no one representing the public interest can even grasp the issues; when the people have lost the ability to set their own agendas or knowledgeably question those in authority; when, clutching our crystals and nervously consulting our horoscopes, our critical faculties in decline, unable to distinguish between what feels good and what’s true, we slide, almost without noticing, back into superstition and darkness.’

Sagan would have been horrified if his editor had said, ‘Carl, perhaps remove the grandchildren line...’

R: Having said that, to an inquisitive child in the 1970s, science was not only NASA and Einstein, but also Bigfoot and the Bermuda Triangle. When not leafing through David Attenborough’s *Life on Earth*, I might be reading *The Unexplained* magazine or *Chariots of the Gods?*, a book that didn’t ask if Neil Armstrong was an astronaut, but went further and asked if God was one.

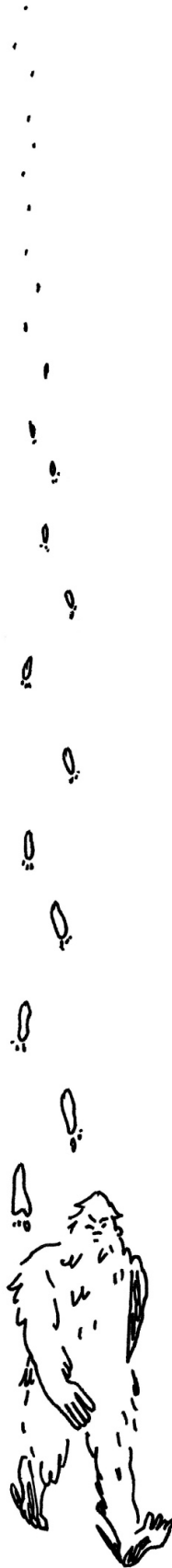
The mind of a curious child was as open to questions of Bigfoot as it was of black holes; at that time, after all, the physical evidence for both was nil.

Made in 1967, the Patterson-Gimlin Bigfoot film was the *Blair Witch Project* of its time, the juddering graininess giving it a disconcerting authenticity. Why juddering graininess makes evidence more persuasive, I have no idea. It looks very like a biggish man in a gorilla costume wandering through a partially cleared woodland, but could it really be so simple?

According to the TV documentary, Chinese scientists had examined the footage and decided a man could not walk in such a lumbering manner. I myself have tried to walk in that way, both in and out of my gorilla costume, and I’ve found it surprisingly easy, but then, that might be evidence of a recessive Bigfoot gene revealing my family’s shameful

Sasquatch dating past. Eventually, evidence-based investigation by author Greg Long revealed the truth of the Bigfoot film.

Retired labourer Bob Heironimus saw a documentary about the 'Bigfoot hoax' in 1998 and decided now was the time to own up that he was the human in the costume, bulked out by American-football shoulder pads and encased in a very smelly and claustrophobic mask that he had not enjoyed wearing at all. Those sceptical of scepticism may consider that this is a typical attempt by the National Parks Service to cover up their family of Bigfoots, but the next stage of investigation reveals the reason why you must avoid using anyone with a prosthetic eye when attempting to pull the wool over other people's functioning eyes. The Bigfoot's right eye reflects sunlight when looking at the camera because Bob had a glass eye. The sceptic sceptic may still declare, 'but how do we know the Bigfoot has not developed glass-eye technology?' and the mystery can continue if they'd like it to.





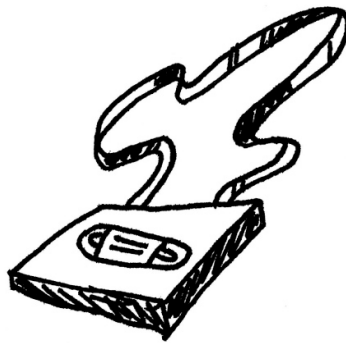
Still from the famous Patterson-Gimlin Bigfoot film made in North Carolina in October 1967.



Wilderness explorer C. Thomas Biscardi claimed to have captured Bigfoot on camera in northern California in 1981. He had been searching for the legendary ape-like creature for nearly a decade.



Another supposed 'sighting' of Bigfoot.



B: We recount this story for two reasons. One is to provide a glimpse into the confused and dusty book repository of Robin's mind, where the windmills cannot turn freely because their mechanisms are clogged with VHS tape.

But it also illustrates what we hope *The Infinite Monkey Cage* is about; seeking evidence for working out why you believe what you believe and

being open to changing your mind if the body of evidence leads to a different conclusion.

R: We currently live in a world where the quantity of information doubles with increasing speed. We can be overloaded by the extraneous. We can be misled by many groups and individuals who project the illusion of authority. For the open-minded and sceptical, the entire day can be lost just trying to work out if the front page of a newspaper is accurate. Dogma can be alluring when open-mindedness is so bewildering. It is troublesome to realise that nothing is 100 per cent right, but there are things which are the least-wrong version of events or ideas. Over the almost 100 episodes of *The Infinite Monkey Cage* we have recorded so far, we have tried as often as possible – whether dealing with race, climate change or cosmology – to demonstrate that the elasticity of an idea is determined by the evidence available. Where there is no evidence, you can stretch an idea as much as you want, but in this case the idea may be of little practical use and not one to inform your decisions.

Of the two of us, I am probably more sceptical when it comes to the views of scientists, though Brian may say that's because I don't understand the equations. We'll explore some of our more incendiary stand-up rows later in the book.

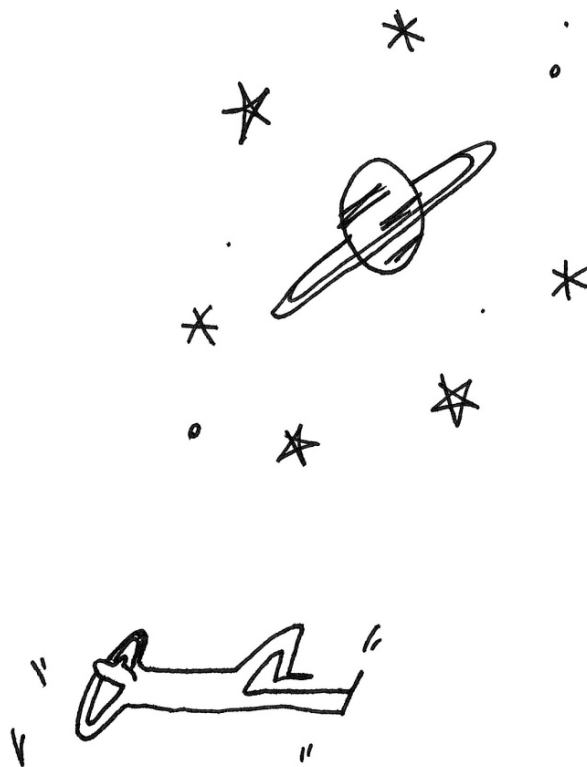
B: I hope that *Monkey Cage* also goes a long way to erasing the myth that science is a cold endeavour, where humans with an emotional range that barely goes from A to B sit and count things and make graphs from the results and then state their discoveries with error bars in a monotone drone. As Albert Einstein wrote, 'with logic we can go from A to B, with imagination we can go wherever we want.' As many of our guests have demonstrated in their work, imagination and passion are vital to understanding. We need to maintain our childhood desire to keep pulling at the threads of our understanding: 'But why? But why? But why?'

'I want a liquid mirror on the dark side of the Moon please. Get one of the really massive craters, and have a really really massive telescope on the dark side of the Moon. Just think what you could do with that!'

Professor Catherine Heymans
Series 16, Episode 1 (3 July 2017)

R: In the radio series we hope to ignite or reignite people's passions. We hope that people finish listening to each episode with a desire to know more and see more, to lie in the grass and look at the stars, to view Saturn's rings through a telescope, to imagine hopeful possibilities for the future and ponder how to remove the obstacles to a better tomorrow.

When we started thinking about this book, we wanted to create an annual just like the *Look and Learn* annuals that excited us as children. This is not a book of conclusions, but it is, we hope, a book of benevolent spikes and spurs that will make you want to look more deeply into the subjects we cover.



**Brian concludes: We are both
fortunate to be in the position of**

making a living from being curious. From the evidence we have so far, it would seem we are a rare species; a species aware of itself and interested in its surroundings beyond the needs of survival. Our ambition is that, one day, this book will be casually discarded on a graphene table amongst the reading materials in the arrivals lounge on Mars.



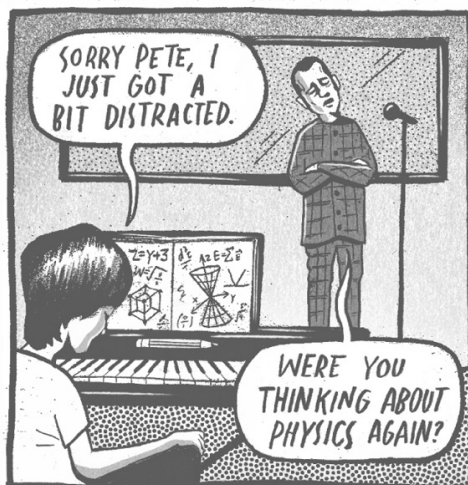
The Mars Pathfinder mission was an important first step in rovers for NASA. A 1997 mission included the first successful rover on Mars, called Sojourner, which spent 83 days of a planned seven-day mission exploring the Martian terrain, acquiring images, and taking chemical, atmospheric and other measurements.

THE BRIAN COX STORY THIS WEEK: 'PRINCE CHARM QUARK'

THINGS CAN ONLY GET ... BRIAN, WHAT ON EARTH ARE YOU PLAYING!?



D'REAM ARE REHEARSING...



SORRY PETE, I JUST GOT A BIT DISTRACTED.

WERE YOU THINKING ABOUT PHYSICS AGAIN?



NO, I WAS...

IT'S WRITTEN ALL OVER YOUR FACE! YOU WERE WONDERING WHY SPIN IS AN INTRINSIC FORM OF ANGULAR MOMENTUM CARRIED BY ELEMENTARY PARTICLES!

BRIAN, THIS CAN'T GO ON. IT'S TIME TO CHOOSE - POP STARDOM OR PARTICLE PHYSICS!



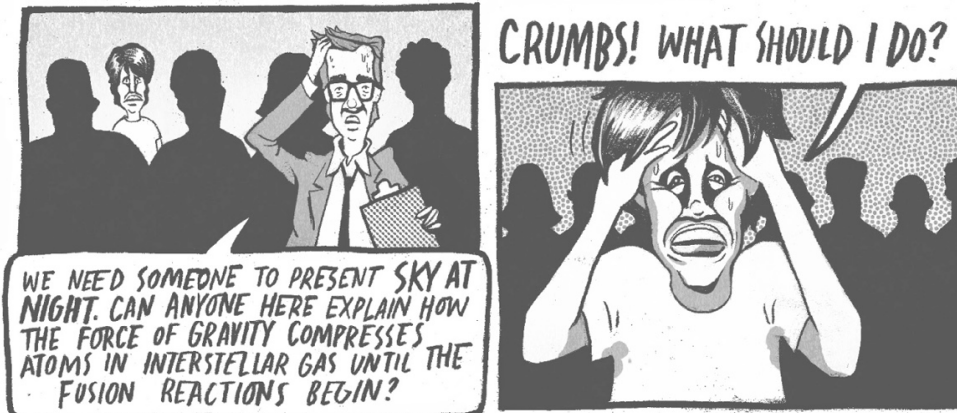
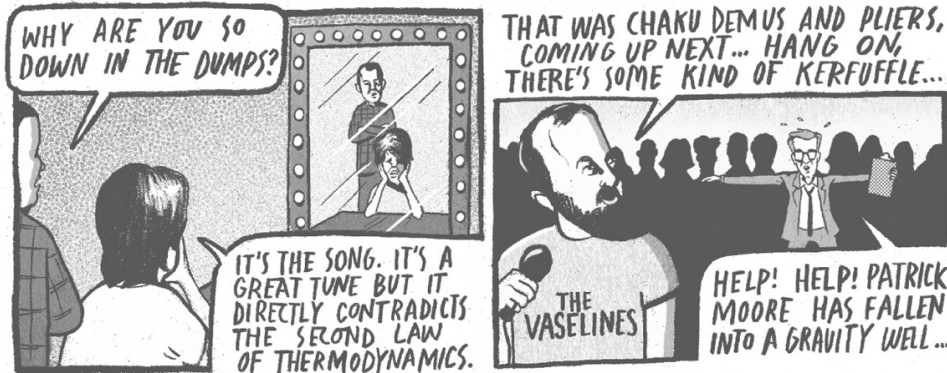
BACK AT BRIAN'S HOUSE...



SOMETIMES I THINK YOU MIGHT BE MY ONLY FRIENDS - WHAT SHALL I DO?

HUMANITY IS DOOMED!

DELETE! DELETE!



NEXT WEEK 'DUELLING XYLOPHONES'-BRIAN AND PATRICK MOORE FIGHT FOR THE RIGHT TO EXPLAIN BLACK HOLE SPAGHETTIFICATION WITH XYLOPHONES.

A QUESTION

Why is the programme called *The Infinite Monkey Cage*?

Someone suggested we called it 'Top Geek'. From that point onwards, we were determined to find an alternative by any means possible. 'Top Geek' suggested a show where Brian got overexcited to the point of Freudian excitement as he test-drove particle accelerators while wearing very tight jeans.

So I sat in a room in Levenshulme with an A4 pad and sought to escape my Richard Hammond fate by dreaming up every possible alternative, writing down every dismal proton pun or alliterative coupling of cosmology and comedy. From Fermat's Penultimate Theorem via Einstein A-Go-Go to Cosmic Asides, the list was many and awful. Sometimes the key to writing is to put everything down, including the horrors that you might have to resort to if your brain doesn't offer you something better.

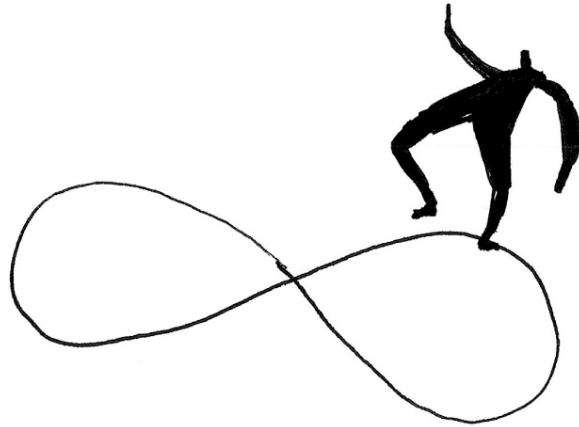
Fortunately, I never got as far as Planckety Planck, Celebrity $E=MC$ Squares or Custard Pi.

In fact I came up with 'Infinite Monkey Cage' quite early on. It was the Sasha's idea to add 'the' at the beginning so that we became more definite – it is always useful in such an uncertain universe to find any way possible of making your existence more concrete, especially when so much of us is just empty space reliant on string forces.

I like thinking about infinity.

I hate thinking about infinity.

It gives me cosmological vertigo.



Apparently this was a new malaise of the late nineteenth century. With the Earth uncentred from the Universe, Darwin showing our familial proximity to chimpanzees and rapidly increasing technological advances, the magnitude of it all became dizzying. So much so that this was given as one of the reasons why Gauguin went to Tahiti and pretended that all its female inhabitants were topless for most of the day.

I can't remember when I first found out about infinity, but it made me wobble every time I thought about it. I would imagine the Universe had existed forever and I would start to topple. I would imagine travelling in a straight line in my pencil-drawn rocket ship and seeing no end in sight.

Eventually I was saved by hearing about the Big Bang, which put the whole idea of infinity into some perspective. At least our universe was now imaginably unimaginably vast.

But then I heard rumours that even with the Big Bang there was still room for a universe of an infinite size with all its associated ramifications. While thinking about that and watching the buses passing through Levenshulme, I thought of all those monkeys writing *Macbeth* or *Titus Andronicus*, as well as *Fifty Shades of Grey*, Delia Smith's *Cooking for One*, the bus timetable for the Number 63 from East Dulwich to King's Cross and all the works of L. Ron Hubbard. I had always been told that an infinite number of monkeys will eventually write the works of Shakespeare, but a jovial and intense mathematician informed me that they won't eventually write the works of only Shakespeare, they will immediately write the works of Shakespeare

and Milton and Dante and Chaucer and Ursula K. Le Guin, and every issue of *2000AD*, *Reader's Digest* and all the titles in the Mills & Boon collection.

I was wobbly again.

This infinity sure seemed big.

So I thought of a cage so big that it contained an infinite number of monkeys – and mused over whether that could even be a cage – and I imagined it as a flippant description of a vast universe. As we were hoping our new show would find time (if time exists) to cover everything in the known universe at least, this seemed like a lightly enigmatic title.

I came up with ‘Infinite Monkey Cage’ quite early on. It was Sasha’s idea to add ‘the’ at the beginning so that we became more definite – it is always useful in such an uncertain universe to find any way possible of making your existence more concrete, especially when so much of us is just empty space reliant on string forces.



HS OLD AND THE POSSESSOR OF SIX TEETH: JUBILEE, THE BABY CHIMPANZEE BORN AT THE "ZOO," BEGINNING TO WALK.



CARES OF MOTHERHOOD: BOO-BOO SCRATCHES HER FOREHEAD OF ANXIETY, WHILE JUBILEE LENDS AN EAR TO M.

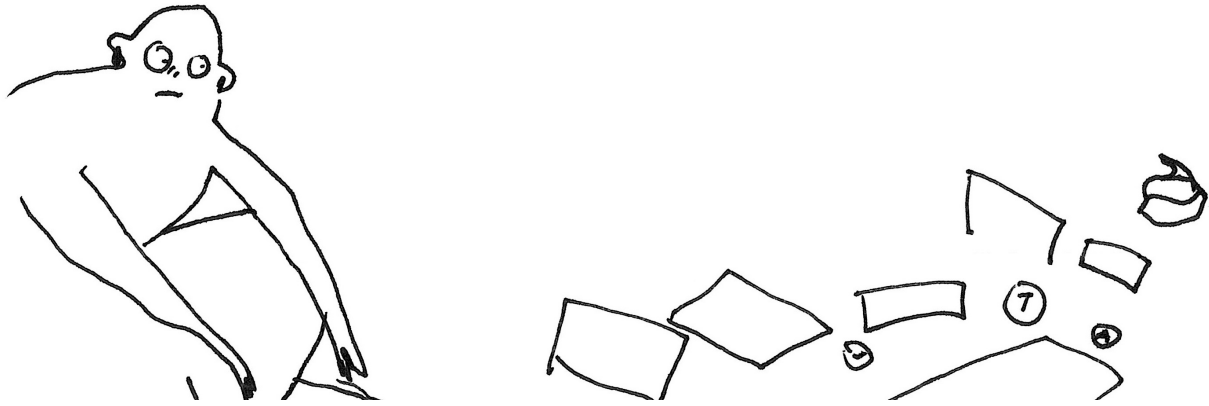


THE YOUNG IDEA": BOO-BOO, THE MOTHER CHIMPANZEE, WITH JUBILEE, SEEMS TO BE URGING JUBILEE TO ASSUME AN UPRIGHT POSITION.



It is an interesting question as to whether the ‘The’ at the beginning of *The Infinite Monkey Cage* is necessary. If we assume that the monkey cage in question is our universe, some important cosmological caveats are in order. Firstly, we do not know whether the Universe is infinite. We can only say that there is more of it than we can see. The part we can see is called the Observable Universe, and it currently contains around 2 trillion galaxies; not an infinite amount of territory for monkeys, but quite roomy. The number of accessible galaxies is falling, however, because we live in an expanding universe. As space stretches, the distance between galaxies that are not bound together by gravity increases. In a few tens of billions of years, the distance to most of the galaxies we see today will be increasing so fast that the light emitted from them will no longer be able to reach us, and conversely we will never be able to reach them. Their images will fade and redden until they are no longer visible. In the far future, the Universe we see through our telescopes will consist entirely of our local group of 50 or so galaxies, which will most likely have merged into a single super-galaxy. Beyond, there will be only darkness. Unless textbooks survive from the distant past, the cosmologists of the future will find it impossible to imagine the scale of the Universe beyond their horizon, or indeed have any inkling that such a thing exists. The accessible part of the cage will consist of a single galaxy, surrounded by a great all-encompassing void.

Secondly, the question arises as to whether there can be more than one infinite cage. It seems that there should only be room for one, but that is not necessarily the case. As we’ll see in the section that discusses [Hilbert’s Grand Hotel](#), infinity is a slippery subject. There is a cosmological theory known as eternal inflation which leads to the idea of an inflationary multiverse. Our universe could be a single ‘bubble’ universe amongst an infinite sea of universes, each with potentially different low-energy laws of nature. Some may contain monkeys, others may not. Grammatically speaking, then, if our reality is really the multiverse of eternal inflation, the prefix ‘The’ may be necessary if we intend to refer to our specific monkey cage, rather than the infinitely many monkey cages that may exist.



From our first episode, we started to get emails and letters with listeners' conjecture on what exactly was meant by an infinite monkey cage. This was on top of the complaint we received from an angry animal rights activist who wrote that 'yet again, the BBC is celebrating animal cruelty and vivisection. Who spends their time imagining monkeys crammed in a cage?' We wrote back to explain that an infinite monkey cage is roomy. We heard nothing more.

By week three, we were receiving letters complaining that the show was another of those arrogant shows that thinks you can prove anything with evidence and that the very title was based on a lie.

'The idea that an infinite number of monkeys would write the works of Shakespeare is rubbish, as a recent experiment has proved.'

This was exciting news. A maverick scientist had gathered together an infinite number of monkeys? Surely we would have heard. It's hard to be surreptitious with an infinite number of monkeys. It's the noise and the smell.

Sadly, the experiment was somewhat smaller. One typewriter and six monkeys at Paignton Zoo. After a month, they had broken the typewriter and done a poo in it, and not so much as a disembowelling scene from *Titus Andronicus* was found. We attempted to explain that six monkeys really wasn't enough, it was too far from an infinite number of monkeys – but to no avail. The correspondent was certain that at the very least it would be an accumulating system:



10 monkeys = a leaflet on banana safety.

100 monkeys = an article for GQ on aftershave.

1000 monkeys = a simian version of 50 Shades of Grey (Langur).

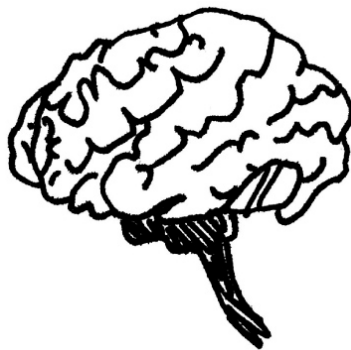
Just as with the complainant who was annoyed that we had no ghosts on the panel for our show, eventually the fury faded into an email memory, to be archived and trashed when in need of a new memory.



INFINITY

‘Infinity always gives me the urge to scratch my head. Perhaps it’s a rash. I worry about infinity, it is much bigger than my brain.’

*Professor Carlos Frenk
Series 10, Episode 5 (5 August 2014)*



First, let us convince ourselves that the concept of infinity makes sense. Consider adding an infinite number of numbers together:

$$\frac{1}{2} + \frac{1}{4} + \frac{1}{8} + \frac{1}{16} + \frac{1}{32} + \frac{1}{64} + \dots$$

This is called a geometric series. At first sight, you might guess that adding an infinite series of numbers together one after the other, forever, should lead to an infinitely large number, but this isn’t necessarily the case. For this particular series, the result of adding them all up is 1. You can see this by using a little simple algebra.

Let’s call the sum of this series S:

$$S = \frac{1}{2} + \frac{1}{4} + \frac{1}{8} + \frac{1}{16} + \frac{1}{32} + \frac{1}{64} + \dots$$

Now consider a different series; the original one, but with each term divided by 2:

$$S/2 = \frac{1}{4} + \frac{1}{8} + \frac{1}{16} + \frac{1}{32} + \frac{1}{64} + \dots$$

Now subtract $S/2$ from S . Every term in the series disappears except the first term in S :

$$S - S/2 = \frac{1}{2}$$

$$\therefore S/2 = \frac{1}{2}$$

$$\therefore S = 1.$$

Adding an infinite series of numbers together is something that we can do, at least in this example, and get a finite answer.

The type of infinity we're thinking about here is an infinite set of fractions; $\frac{1}{2}$, $\frac{1}{4}$, $\frac{1}{8}$, and so on. How many of these fractions are there? An infinite number, and we assumed this in our proof because for every fraction in the infinite series S , other than $\frac{1}{2}$, there was a corresponding fraction in the infinite series $S/2$ to cancel it out. But this raises an interesting question. We subtracted an infinite number of fractions from an infinite number of fractions and we had one term left: $\frac{1}{2}$. Does this mean that there was one more fraction in S than in $S/2$? The answer is no; the two infinities are precisely the same. The first mathematician to think about what we mean when we speak of an infinite set of numbers was the German mathematician Georg Cantor, at the end of the nineteenth century.

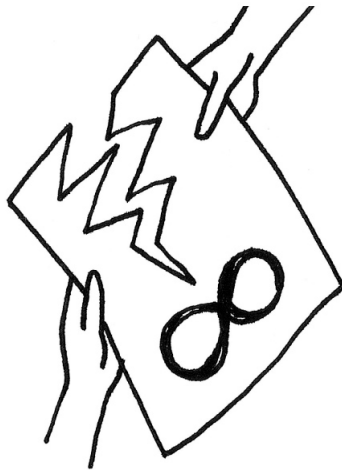


Consider, for example, the set of all integers; 1,2,3,4 ... We could imagine making a table of the integers by writing them all down in a vertical column from 1 to infinity. We could then write each of the terms in our set S alongside in a neighbouring vertical column. Each fraction – $\frac{1}{2}$, $\frac{1}{4}$, $\frac{1}{8}$ – would be paired up with an integer, all the way down the list. We could do the same for our set $S/2$; the column would begin with $\frac{1}{4}$ rather than $\frac{1}{2}$, but it would carry on all the way to infinity. This one-to-one correspondence between all three sets of numbers is the reason why Cantor claimed that the three sets have the same ‘infinity’ of numbers contained within them. Mathematicians would say that the sets have the same cardinality.

There is certainly something odd about these infinite sets, because they don’t behave as we might expect. Notice, for example, that the set $S/2$ is a subset of S , because S contains every entry in $S/2$, but it also contains $\frac{1}{2}$. And yet S and $S/2$ are the same size! This counter-intuitive nature of infinite sets led to one of the great *Infinite Monkey Cage* arguments that took place between Brian and comedy producer John Lloyd in the form of Hilbert’s Grand Hotel paradox.

John Lloyd: Infinity plus one is just intellectual brain bending and I cannot see the use of it. Infinity is a word. That belongs to the

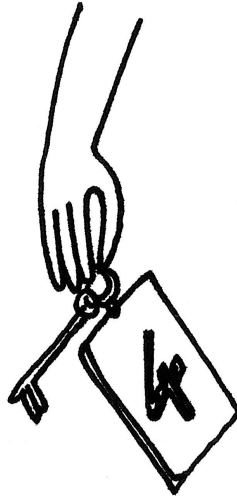
wordy people like me and Robin. The point is you cannot place a numerical value to infinity and therefore you cannot add a plus one to it or a minus one.



Brian: There are either an infinite number of numbers or there aren't. I don't see what the problem is?

John: There aren't an infinite number of numbers, because you can always have more than infinity and so infinity is a meaningless concept.

Series 9, Episode 4 (9 December 2013)



Hilbert's Grand Hotel has infinitely many rooms, and they are all occupied. What happens if a further guest turns up unannounced? The guest in Room 1 can be moved into Room 2, the guest in Room 2 can be moved into Room 3, and so on, freeing up Room 1 for the new guest. There is always room in Hilbert's Grand Hotel, even when it is full. We haven't increased the size of the hotel, and yet we've accommodated another guest. Using the language above, we can say that the cardinality of the set of rooms in Hilbert's Grand Hotel is the same as the cardinality of the set of guests. Notice that this implies that we can slot an infinite number of extra guests into Hilbert's Grand Hotel, even when it is full. To see this, note that we could have moved the guest in Room 1 to Room 2, the guest in Room 2 to Room 4, the guest in Room 3 to Room 6, and so on. This frees up ALL the odd-

numbered rooms, and since there are an infinite number of odd numbers, the Grand Hotel can now accommodate an infinite number of new guests. The reason for this strange state of affairs is that the number of odd rooms is not smaller than the number of even + odd rooms. Both sets have the same cardinality.

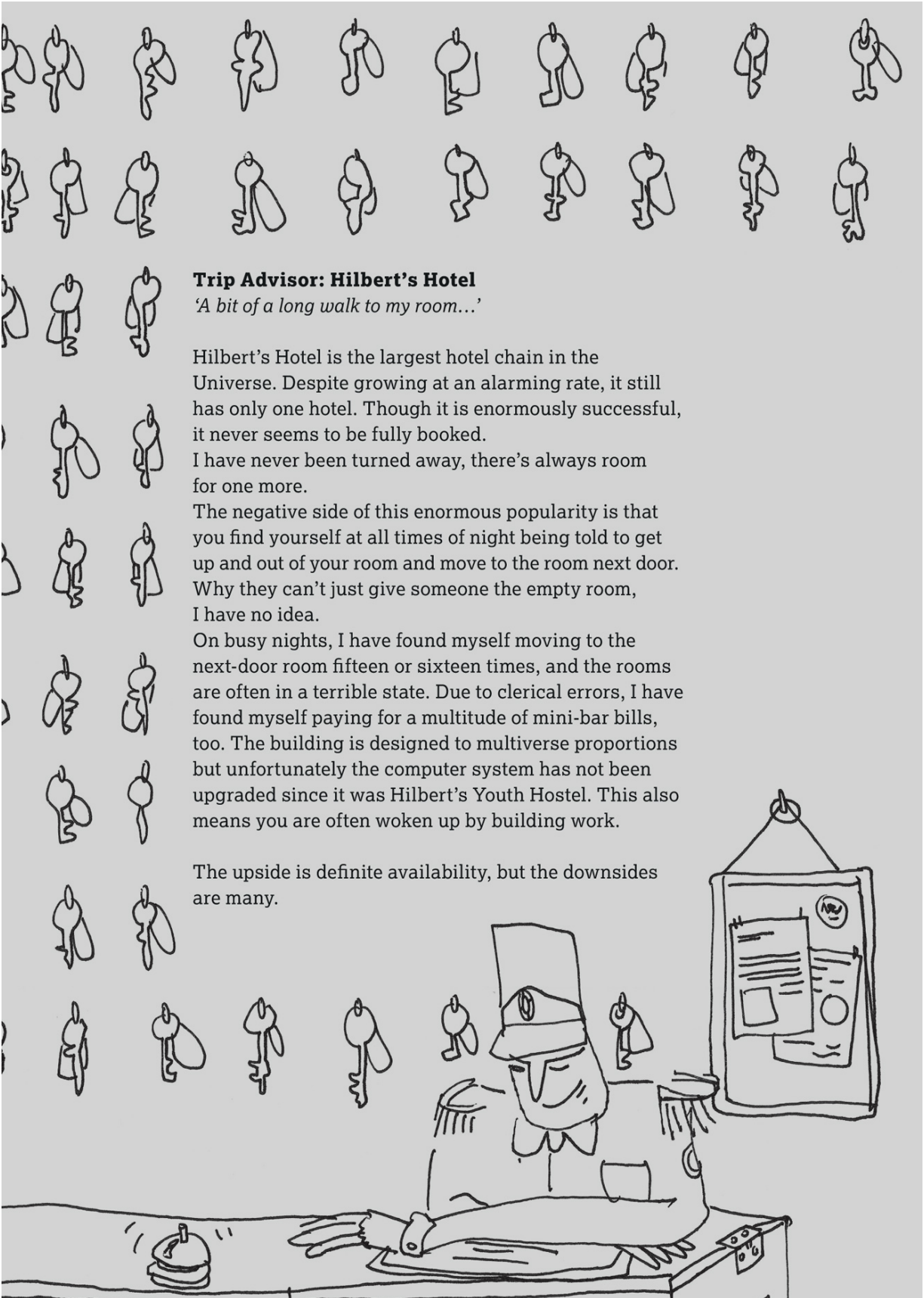
s_1	=	000000000000 ...
s_2	=	111111111111 ...
s_3	=	010101010101 ...
s_4	=	101010101010 ...
s_5	=	110101101010 ...
s_6	=	001101101110 ...
s_7	=	100010001000 ...
s_8	=	001100110011 ...
s_9	=	110011001110 ...
s_{10}	=	110111001011 ...
s_{11}	=	110101001000 ...
.	
.	
.	
s	=	101110100111 ...

Figure 1

As an aside, there are sets with a different cardinality to the integers. Consider, for example, the set of infinite binary sequences; 0000000000..., 1111111111..., 0101010101... and so on. Cantor imagined laying these out in a vertical table, just as we did for our sets S and $S/2$, against the column of integers. Now imagine constructing a new binary sequence by changing all the digits in a diagonal line down the table; when there is a 1, swap it for a 0, and when there is a 0, swap it for a 1 (see [Figure 1](#)). The resulting sequence is not in the table; it can't be the same as the sequence in the first row because the first digit has been flipped. It can't be the same as the sequence in the second row because the second digit has been flipped, and so on. Every row will differ from the new sequence by at least one digit, claimed Cantor, because there are more infinite sequences of 1s and 0s than

there are integers. A mathematician would say that the infinite set of binary sequences has a cardinality greater than the set of integers.

Infinity exists in mathematics, and as we have seen there are different sorts of infinity. We might ask whether there are infinities in the real world, and the answer is that we don't know. The Universe may or may not be infinite in extent. The part of the Universe we can observe is certainly finite, and cosmologists refer to this as the Observable Universe. The most distant objects we can see are objects from which light has been able to travel during 13.8 billion years, which is the age of the Universe. You might be tempted to say that the Observable Universe is 27.6 billion light years across, but this is not correct because the Universe has been expanding throughout this time, and the objects have receded from us. Because we know how much the Universe has expanded, we can calculate the diameter of the Observable Universe today; it is just over 93 billion light years.



Trip Advisor: Hilbert's Hotel

'A bit of a long walk to my room...'

Hilbert's Hotel is the largest hotel chain in the Universe. Despite growing at an alarming rate, it still has only one hotel. Though it is enormously successful, it never seems to be fully booked.

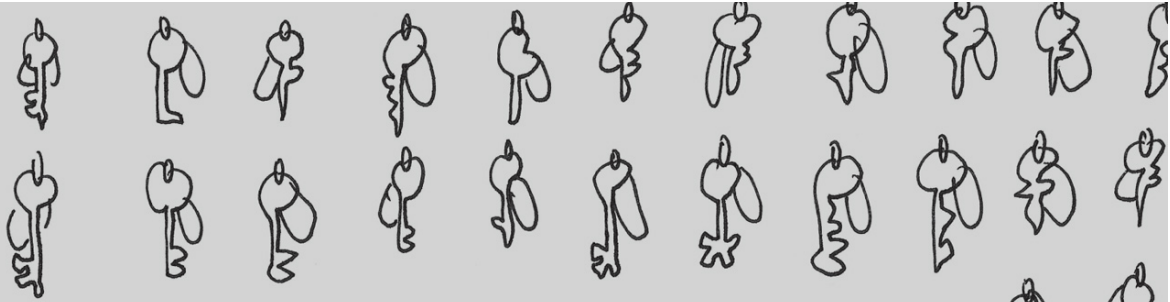
I have never been turned away, there's always room for one more.

The negative side of this enormous popularity is that you find yourself at all times of night being told to get up and out of your room and move to the room next door. Why they can't just give someone the empty room, I have no idea.

On busy nights, I have found myself moving to the next-door room fifteen or sixteen times, and the rooms are often in a terrible state. Due to clerical errors, I have found myself paying for a multitude of mini-bar bills, too. The building is designed to multiverse proportions but unfortunately the computer system has not been upgraded since it was Hilbert's Youth Hostel. This also means you are often woken up by building work.

The upside is definite availability, but the downsides are many.





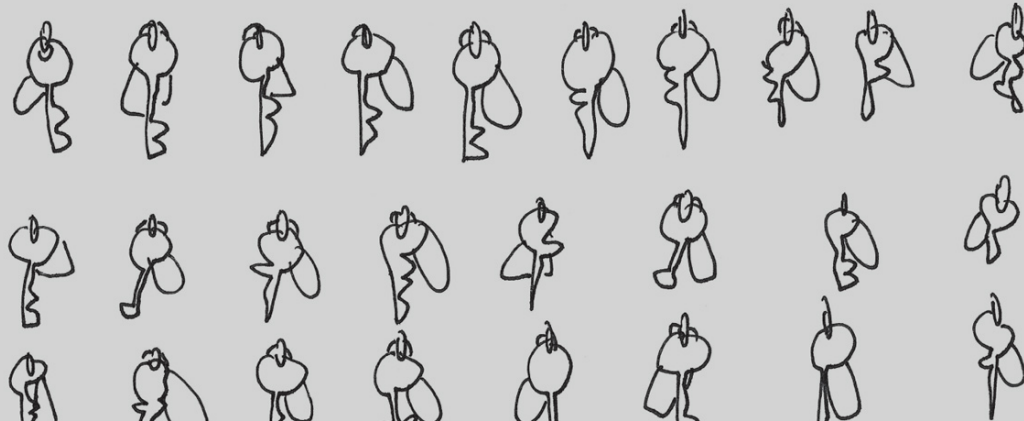
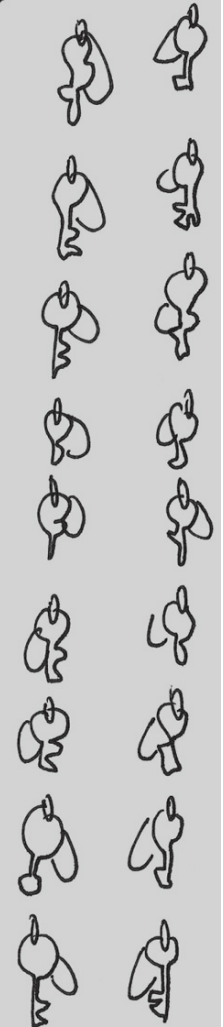
On a recent trip, I decided to leave my family in the lobby while I popped our bags in the room. No one informed me that, due to extensions, the elevator now travelled near light speed. By the time I returned to the lobby, my wife was dead and my five-year-old was in his late 90s. Clearly, I am not the only one to have made this mistake as they have recently started a crematorium service, conveniently placed between the spa and the 24-hour carvery. The carvery has also gone downhill, partly because the smell of the crematorium seems to mix with the rotisserie Soylent Green. On the plus side, the chef has also recently added Soylent Blue, Soylent Red and Soylent Mauve, though that tastes a bit man-made.

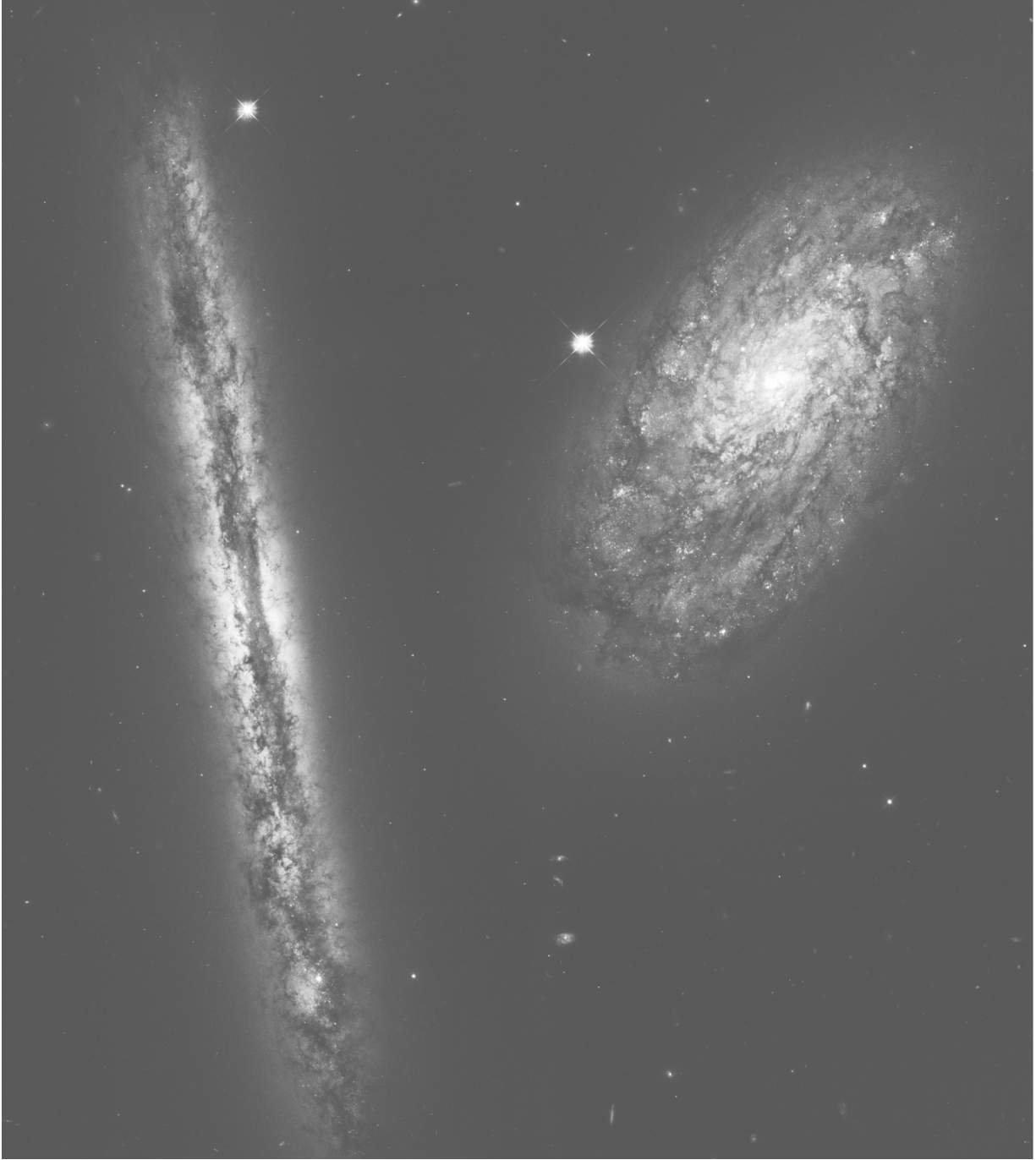
The service can be very slow at breakfast, and confusing, too. The other day I was served dinner by me, or rather another me. The breakfast buffet queue is often very long.

This reminded me of the many checking-out problems there have been, with a number of people having the same name and face as me.

All in all, not a bad a hotel, spoilt by the death of my wife, but the kippers are excellent.

The Wi-Fi is patchy.





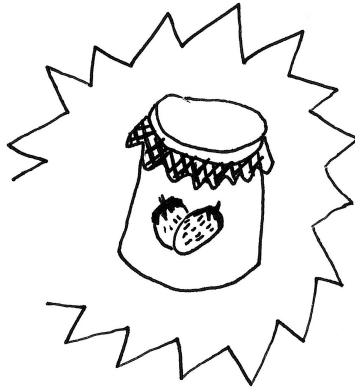
There are around 2 trillion galaxies in this observable sphere centred on the Earth, but this is very likely to be a small fraction of the entire Monkey Cage. Whether it is a finite subset of an infinite cage is an open question.



DEATH, WHERE IS THY PUDDING?

‘In many ways, Schrödinger’s Strawberry changed my life. Or death. Or whichever – it’s so hard to tell these days. All I know is the episode which featured that singular fruit gave me and my career a new lease of life. Or death. Oh god...’

Katy Brand, comedian



In the history of human thought, there are a few philosophical questions that become eternal.

Can we ever truly experience reality?

Why is there something rather than nothing?

When is a strawberry dead?

For some reason, neither Plato nor Nietzsche took time to consider the strawberry. Nietzsche’s madman ran into the town square declaring that God was dead, but made no mention of the strawberry – and what of the plum, peach and gooseberry?

It took Professor Cox to contemplate the strawberry.

In a rare moment when he was distracted from thinking about subatomic particles and Hawking radiation, Brian’s brain accidentally allowed a thought about strawberries on a level above muon and lepton.

*Could it be that his jam was in a superposition?
Schrödinger's Compote?*

And if there is Schrödinger's strawberry compote, does that also mean we should be investigating Planck's raspberries and Heisenberg's goji berries? Should market gardeners be looking at their fruit at a quantum rather than molecular level?

We were discussing levitating frogs. Andre Geim is a rarity in the scientific world, being a winner of both the Nobel and Ignoble Prizes. His Nobel Prize in Physics was awarded for discovering a method to isolate a single layer of graphite atoms and thus create graphene, the thinnest and strongest material in the world. His frog levitation took place a decade before. Geim levitated frogs to demonstrate diamagnetism. Biologist and maggot expert Matthew Cobb explained the experiment. He told us it wasn't really about the frog, though don't tell that to the frog, they are very egotistical, especially the Poison Dart frog, which does not take criticism well. The experiment was about quantum mechanical effects; Geim also used water and 'dead strawberries'.



*Brian's Vulcan ears pricked up like those of a German Shepherd.
He was perplexed. 'What qualifies a strawberry as being dead?'*

It is here that the potential melancholy of jelly and the funereal possibilities of the trifle began.

What pathologist has the correct qualifications to declare a strawberry dead?

Animals are much easier than fruit to pronounce dead. The clues seem simpler: no heartbeat, no breathing, no eating, no movement. Even that may not offer certainty though.

Rana sylvatica is a species of wood frog (two frog mentions already, this should keep the frogs on side) that has 'extreme freeze tolerance'. Species with this attribute can survive when two-thirds of their body water is frozen. *Rana sylvatica* also stops breathing and has no heartbeat for days at a time. Life is notoriously hard to define. Every time you think you've come to a neat definition, some philosopher or other will pipe up, 'ah, but isn't that also the property of fire?' Then, when you redefine, they'll say, 'ah, but isn't that the property of crystals?' Eventually, rather than define life, you want to take one.

Death must be easier to define.

Questions of life and death, whether on the scale of amoeba, strawberries or physicists demonstrates the complexity of living things and the difficulty of defining what it is to be alive.

For the physicist, the question becomes 'how do you write the wave function of strawberry?'

According to the work of the French, Nobel Prize-winning physicist Louis De Broglie, it will have a wave length.

The definition of a dead strawberry became slippery. In the simplest terms, Professor Nick Lane stated that if it's not continually harnessing energy to maintain being alive, it's dead. The ability to harness energy seems to offer one of the most rewarding views of defining what is alive.

Professor Nick Lane: We need an enormous amount of energy to live... if you put a plastic bag over your head you'll be dead in a minute and a half.

Brian: No, but I put strawberries in bags all the time and carry them back from the supermarket.

Robin: Can I just say he doesn't come back from the supermarket with strawberries, he has a man that works for him who comes back with the strawberries from the supermarket...

Series 8, Episode 1 (24 June 2013)



So how do you murder a strawberry?

Whether boiling or freezing it, you are preventing the seed from ever germinating, curtailing the potential of the strawberry and yet increasing its potential too. Who wants to be a live and unknown strawberry when you could be a celebrated dead one smeared on a scone in Torquay? For a strawberry, a frog or a human, that is the key to life over death: do you still have potential? This page is in memory of all the strawberries that have died for us. Your death was delicious.

Brian replies...



Strawberries are inaccurately named, counter-intuitive things. The strawberry is not a berry: the red fruit is part of the stem of the plant from

which the flower organs grow. The things we call the seeds – the little pits on the fruit – are not seeds, they are the plant's ovaries, and the seeds reside inside. So is a strawberry dead or alive?



In the original episode of *The Infinite Monkey Cage* where I first posed the strawberry death question, Professor Matthew Cobb, from the University of Manchester, answered, 'As soon as you pick a strawberry, it's dying. As it decays it increases its sugar content, and that is what makes it sweet, but essentially it is dying.' This is correct for the berry as a whole, which is a part of the plant and will decay if it isn't attached. The strawberry no longer has access to the supply of ordered energy from the Sun that a plant uses to maintain its structure through photosynthesis, and the Second Law of Thermodynamics does the rest.





The Second Law of Thermodynamics is arguably the only law of nature that we currently possess that is actually a law, which is to say physicists believe that it is absolutely right. Quantum Theory and General Relativity may one day be refined or even replaced, but the Second Law of Thermodynamics will surely still stand. It states that, over time, an isolated system will become more disordered. In simple terms: Things Can Only Get Worse.



If a teacup falls to the ground, it smashes into pieces, and we never see the pieces spontaneously reassemble into a teacup, even though there is nothing in the laws that govern the motion of the constituent molecules that prevents it. The reason is that there are many more ways of arranging the molecules such that they form a pile of bits on the floor than the very specific arrangement that makes a teacup. A teacup is an unlikely arrangement of molecules, given that all arrangements are equally likely.

Living things certainly seem to run counter to this law. A strawberry is one of the most complex things we know of in the Universe, and it is at first sight hard to see how this can be squared with the Second Law. This has become known as Schrödinger's Paradox. The resolution to the paradox is

relatively straightforward. The strawberry is not an isolated system: when the strawberry is attached to a living plant, it is part of a system that includes the heat of the Sun and the coldness of space. The Sun is a source of high-energy photons cascading down onto the leaves. The plant absorbs these photons and uses their energy to convert carbon dioxide and water into sugar and oxygen through photosynthesis. Sugar is more complex than carbon dioxide and water; the atoms have been rearranged into a more ordered structure, just like a teacup. This is not all that happens, however. The plant radiates heat out into its surroundings, which is in turn radiated into the coldness of space. Heat is also a stream of photons, but they are lower energy and more numerous than those in the incoming sunlight. Heat is a highly disordered form of energy, and when all the sums are done, it turns out that this more than compensates for the increase in order during the formation of sugars and the other intricate structures of the strawberry. We might say that the strawberry increases the amount of disorder in the Universe quicker by the very fact of its existence, thus hastening the demise of all of creation. It borrowed order from the Sun, but increased the disorder of the rest of the Universe as a result.

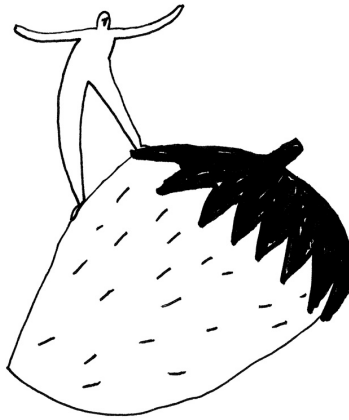


The moment that the strawberry's metabolism grinds to a halt, it can no longer function as a little machine sitting between the cascade of ordered energy from the Sun and the coldness of space, and the Second Law reasserts its grip. This is death.



The seeds inside the ovaries attached to the fruit are a different matter, however. They are alive if they are capable of germinating. Seeds can stay dormant for very long periods of time; many decades in some instances, and there are different types of dormancy in the plant kingdom. The strawberry seed exhibits physical dormancy, which means that the seeds' outer casing, being impermeable to water, prevents the embryo within germinating – germination is defined as the sprouting of the seedling from the seed. When the strawberry is eaten by an animal, the seeds pass through the digestive tract and the outer casing is damaged such that it becomes permeable to water. This begins the germination process. In other species, the outer casing can be damaged by fluctuating temperatures, freezing and thawing, drying, or even fire. The evolutionary advantage of delayed germination is clear; there is a selective advantage to delaying germination until the onset of the rainy season in the tropics, for example. Awaiting dispersal via consumption by an animal can also be seen to offer a selective advantage.

Precisely how physical dormancy evolved, however, is a matter of ongoing research.



Some seeds exhibit a different form of dormancy known as physiological dormancy, in which embryo growth is prevented by inhibiting chemicals. All gymnosperms – of which conifers are the most common group – exhibit physiological dormancy. Unlike physical dormancy, physiological dormancy can be reversible.

The definition of a dead strawberry is therefore a slippery one, and depends on whether you mean the strawberry itself (which is not a berry), or the seeds it contains. In the simplest terms, Professor Nick Lane, from University College London, stated that if the strawberry is not continually harnessing energy to maintain being alive, it's dead. Seeds can continue to metabolise, albeit extremely slowly, whilst dormant. They are therefore alive, until they stop.

Brian noted that our understanding of the plight of a strawberry might be further complicated by taking quantum theory into account, extending the discussion to Schrödinger's Strawberry.

R: I'll tell you what, we'll put a strawberry in a box and we won't observe it and it can be both.

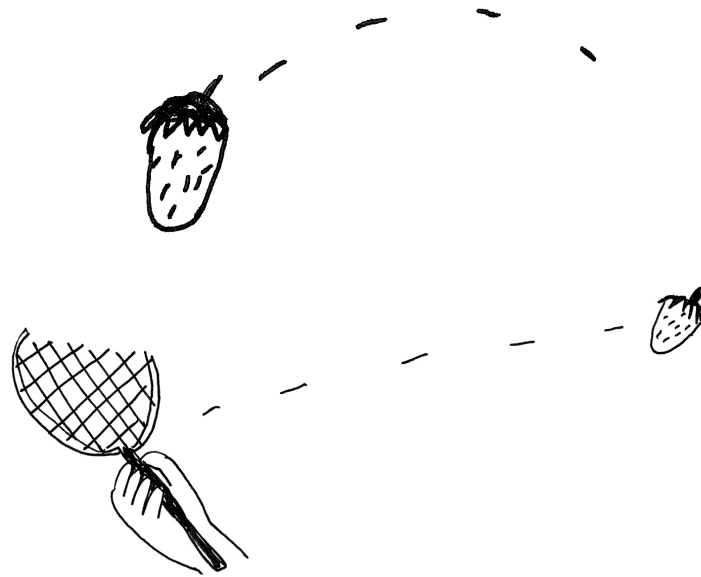
Katy: I love the idea of Schrödinger's Strawberry.

R: The whole of Wimbledon changes.

B: I'm thinking about how you'd write down the wave function of a strawberry.

R: When are you not thinking of a wave function...?

Series 7, Episode 2 (26 November 2012)



Consider a strawberry in a sealed box with a small thermonuclear bomb triggered by the decay of a single radioactive nucleus sufficiently powerful to completely vaporise the strawberry, but not the box. Quantum theory allows us to calculate the probability that at a given time after the box is closed, the radioactive nucleus will have decayed, thus triggering the death of the strawberry.



Until we observe the nucleus (although see below), quantum theory informs us that we are to treat the nucleus as being in a mixture of both 'decayed' and 'not decayed'. Physicists call this mixture a linear superposition. The

amount of ‘decayed’ and ‘not decayed’ changes over time in a way that we can calculate using the Schrödinger Equation, but crucially this is all we can do. The nucleus hasn’t decayed or not – it is simply in a linear superposition.



Since the decay of the nucleus determines the fate of the strawberry, we should also say that the strawberry is in a linear superposition of alive and dead before the box is opened, just like the nucleus. In the form of an equation, a physicist would write:

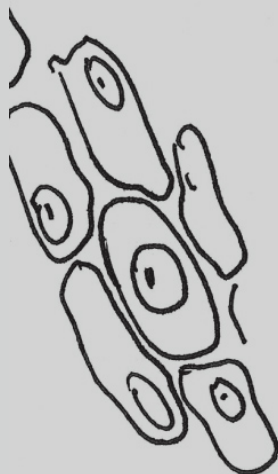
$$| \text{strawberry}(t) \rangle = a(t) | \text{strawberry}_{\text{ALIVE}} \rangle + b(t) | \text{strawberry}_{\text{DEAD}} \rangle$$

There appear to be two problems with this description. Firstly, we need to be clear what we mean by ‘observe’. What is so special about observation that it reduces the linear superposition to the certainty of one outcome or another? Why does the strawberry’s experience not count as an ‘observation’ of whether the radioactive nucleus has decayed? What if we replaced the strawberry by Robin Ince? Would he remain in a superposition of alive and dead until we opened the box?

Secondly, the idea that a strawberry can *only* be in some combination of alive *and* dead in such an experiment and not one *or* the other doesn’t correspond to our perception of reality; surely the strawberry cannot be simultaneously both alive *and* dead before we open the box?

There is an interpretation of quantum theory known as the Many Worlds Interpretation that addresses both these issues. It is the simplest interpretation of the theory, and states that the superposition is never broken. All that happens when we open the box is that we enter a superposition with the strawberry and the nucleus. We might say that there are ‘worlds’ in which we see a vaporised strawberry and ‘worlds’ in which we don’t, but this language is really misleading. Reality is a superposition of all possibilities – and the interesting question becomes why our experience is of a reality consisting of only one set of possibilities. The answer is that the two ‘branches’ of reality following our interaction with the strawberry box evolve separately to each other; they do not interfere and nothing in the future of each branch is contingent on things happening in the other branch. In the Many Worlds Interpretation of quantum mechanics, however, both branches are equally real. The terminology that has developed is to refer to these branches as ‘different worlds’, but that’s misleading. There is only one ‘world’, and it is a world in which everything that can happen does happen and everything is in a superposition with everything else. There are parts of reality in which we opened the box and saw a strawberry, and parts of reality in which we opened the box and saw only vapour. The reason we are unaware of the true ensemble of alternative possibilities in practice is because they have no discernible influence on our experience in a particular branch.





In response to the Great Dead Strawberry Debate, *Monkey Cage* regular Professor Nick Lane sent us this contribution:



Strawberries really are in a superposition of states, although unlike Brian I'm not thinking about quantum states: parts are alive and parts are dead. We tend to think of death as a digital process: we are either alive or dead. But even when a person dies, many of their constituent cells are still alive. These will die in time, because they don't get the services they need to remain alive. Our cells need a lot of services because they have a lot to do – we are high-energy beings, so when the energy flow ceases, we die fast. Strawberries are not: their cells don't have all that much to do, so they can persist much longer before being pronounced dead. The seeds themselves, nicely shrink-wrapped in their own personal ovaries, can persist for years because they've been practically switched off altogether. They're dried out carefully – turned to glass! – without losing their nanoscopic structure. That means their metabolism – the process of living – can be kick-started again when they germinate. The Second Law itself is put on hold, for a while, because the shrink-wrapped state seriously restricts the number of alternative states that they are free to access. I hate to say it, but the chemistry trumps physics, if only for a while. As long as the seeds

don't lose their structure they can switch on again and grow when water is restored. So the most valuable parts of the strawberry are still alive and the rest is just a doomed vehicle at the service of the next generation. Aren't we all?

A Further Frog Footnote



Zoologist Lucy Cooke, whose fruit work includes playing a dancing raspberry in the TV series *The Smell of Reeves and Mortimer*, was fascinated by poison frogs from an early age; in particular, the Golden Poison Frog. Appearing on a *Monkey Cage* about toxins, venom and poison, she told us of her quest to see one. Its poison, an alkaloid poison, is so powerful it will kill you in three minutes, and for the last minute, you'll be in such a state of petrification you will look, to all purposes, to be quite dead already. You only need to touch it and your fate is sealed. While making a TV documentary, she finally came face to face with one. Heavily gloved and visored, she held one in her hand. The rush from her childhood desires being fulfilled, a tear came to her eye. As the frog departed her hand, she put her hand to her eye to wipe away the tear. NOOO!' yelled the crew and she realised that she was millimetres away from joining those who have died for the love of a frog. Now Lucy lives her life wondering if it is better to live to old age or die young and be memorialised as a zoologist who died due to the overwhelming and potential toxicity of the natural world.



Nick Lane: Without death there wouldn't be evolution at all. All the magnificent things in this world are as a result of death, and without it they wouldn't be here. From a non-religious point of view, it's glorious because of death.

Professor Sue Black: And if death is such a great thing, why are we so scared of it? I think it's a wonderful thing. It's the last adventure. No one knows what's coming. Bring it on!

Series 8, Episode 1 (24 June 2013)

AN INTERLUDE

Darwin's worm



‘The sight of a feather in a peacock’s tail, whenever I gaze at it, makes me sick!’ wrote Charles Darwin in a letter to Asa Gray.¹ He went on to write that this was countered by Asa’s story of the black pigs of the Everglades that had evolved to be able to eat a plant root that made the hooves of all other coloured pigs drop off. It seems that Darwin considered the peacock to be weighed down by excessive evolutionary cost compared to the seeming pragmatism of the black pigs.

Charles Darwin had a mind to envy but a physical constitution that few would aspire to. He was hampered by ill health throughout much of his life after his voyage on the *Beagle*. Having spent five years travelling across the world, Darwin lived out the rest of his life in England, mainly in his house in Kent where he mulled over what he had seen and started to understand what it meant, breaking up the day by boiling pigeons to the bone and taking walks around his thinking path. Geneticist and snail expert Steve Jones, a regular guest on *Monkey Cage*, when asked which of Darwin’s books could be avoided by the casual reader said, ‘Don’t read his books about barnacles, he became overly obsessed.’

This still leaves you with books about orchids, emotions, coral reefs and occasional baboon behaviour interludes, as well as, of course, *On the Origin of Species*. Darwin studied every part of the animal world, including his own children: ‘I repeatedly observed my own infants, from under the age of one week to that of two or three months, and found that when a screaming fit came on gradually, the first sign was the contraction of the corrugators, which produced a slight frown, quickly followed by the contraction of other muscles around the eyes.’ Darwin was most definitely an attentive father, but he may have let his children cry for a little while longer for the purposes of research. By reading Darwin you will find out that blue-eyed cats are deaf, bald dogs invariably have bad teeth and that it is quite pointless to try to train yourself to stop flinching when a Puff Adder attempts to strike (he experimented with this in the safety of the reptile house at London Zoo).

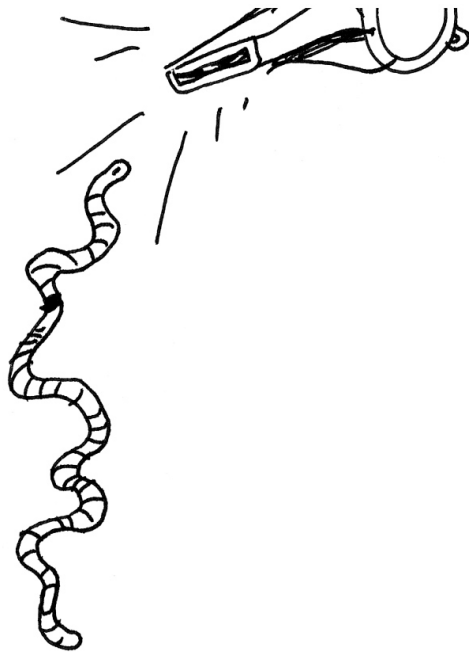


We are now so used to seeing the world and its enormous variety of species on television that it is easy to forget how exotic and strange much of our planet seemed before mass communication. When Darwin was on the *Beagle* he was experiencing things that had barely been imagined by other humans. On 28 February 1832, he wrote of his day in the rainforest: 'The delight one experiences in such times bewilders the mind, if the eye attempts to follow the flight of a gaudy butterfly, it is arrested by some strange tree or fruit; if watching an insect one forgets it in the stranger flower it is crawling over, if turning to admire the splendour of the scenery, the individual character of the foreground fixes the attention. The mind is a

chaos of delight, out of which a world of future and more quiet pleasure will arise.'

We may not have ready access to a rainforest, but it is important to remember that however mundane your environment may seem to be, the life you see in it and the lives of the creatures that exist inside it are remarkable examples of a planet that has more ways of assembling atoms into different forms than any other we know of. Stare out of your train window at the hills and think of all the life before you, some visible – trees and grasses, a possible cow, rabbit or alpaca – many others invisible. You don't need a rainforest for a chaos of delight.

Though many of Darwin's books explored the exotic, as well as pigeons, his final book was on earthworms, *The Formation of Vegetable Mould Through the Action of Worms with Observations on their Habits*. Some may consider that this doesn't sound like one of his speedier page-turners, and they would be wrong. This is the *Monkey Cage's* favourite book about earthworms and we have read three (this is the only one that is non-fiction, though, the others are *Superworm* by Julia Donaldson and Tim Curran's novel *Worm*, about killer worms escaping the sewer and wreaking havoc). We love it for the delight of seeing an elderly man whose curiosity about living things has not dimmed with age.

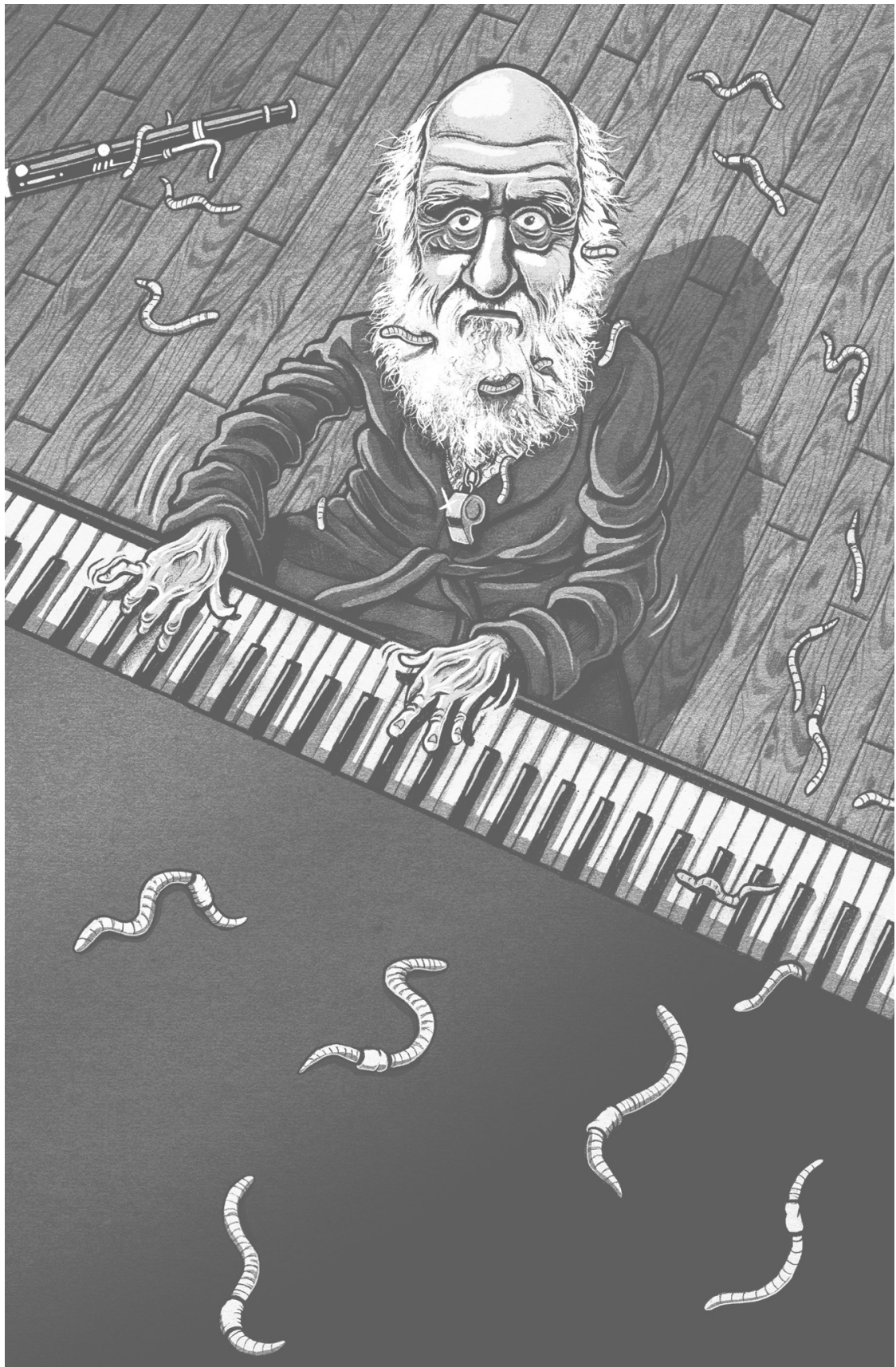


It contains some of my favourite experiments, each one conceived to understand the earthworm a little more. Darwin saw that, like so many living things, this simple creature performed vital functions. Darwin's experiments included breathing on worms after chewing on a variety of different things – from tobacco to perfumed cotton wool – to examine their sense of smell, and putting hot poker near them to see how sensitive to heat they were. It is his experiments on earthworm hearing that I enjoy most, though. He begins with a metal whistle 'which was repeatedly sounded near them'. Seeing no result, some scientists may have stopped there, but not Darwin. Next up, he brought out the bassoon, which they also took no notice of. 'They were indifferent to shouts' and 'when placed on a table close to the keys of a piano, which was played as loudly as possible' there was similarly no reaction. This series of experiments may well have been how they invented jazz. They were reactive to vibrations; this was discovered by placing them on the piano 'and the note C in bass clef was struck', which caused the earthworm to retreat. Darwin then tried the note G, 'above the line in treble clef', and had a similar result.

Darwin's summary of the worm contains his usual mix of beauty and wonder at living things:

'When we behold a wide, turf-covered expanse, we should remember that its smoothness, on which so much of its beauty depends, is mainly due to all the inequalities having been slowly levelled by worms. It is a marvellous reflection that the whole of the superficial mould over any such expanse has passed, and will again pass, every few years through the bodies of worms. The plough is one of the most ancient and most valuable of Man's inventions; but long before he existed the land was in fact regularly ploughed, and still continues to be thus ploughed by earth-worms. It may be doubted whether there are many other animals which have played so important a part in the history of the world...'

Now gather up your bassoons and prepare to experiment, your garden awaits.



¹ A renowned American botanist (1820–88).



No.3

Recipe to Build a Universe



INSIGNIFICANCE

A perspective

There is a problem of insignificance when looking at the night sky. It takes four years for the light from the closest star to Earth, Proxima Centauri, to reach us.

It takes over 16,000 years for the light from the furthest star visible with the naked eye, V762 Cas in the constellation of Cassiopeia, to reach us. The light we see is older than our civilisation.

The Milky Way is a hundred thousand light years across, and it is one of billions of galaxies. You can understand that when dealing with such

magnitudes, people can feel like specks, less than specks, barely the dust of our universe.

During every series of *Monkey Cage* we receive emails and letters from people questioning their own significance after being bamboozled by a cosmological episode.

‘I wish I’d never looked through that telescope, now I feel insignificant.’

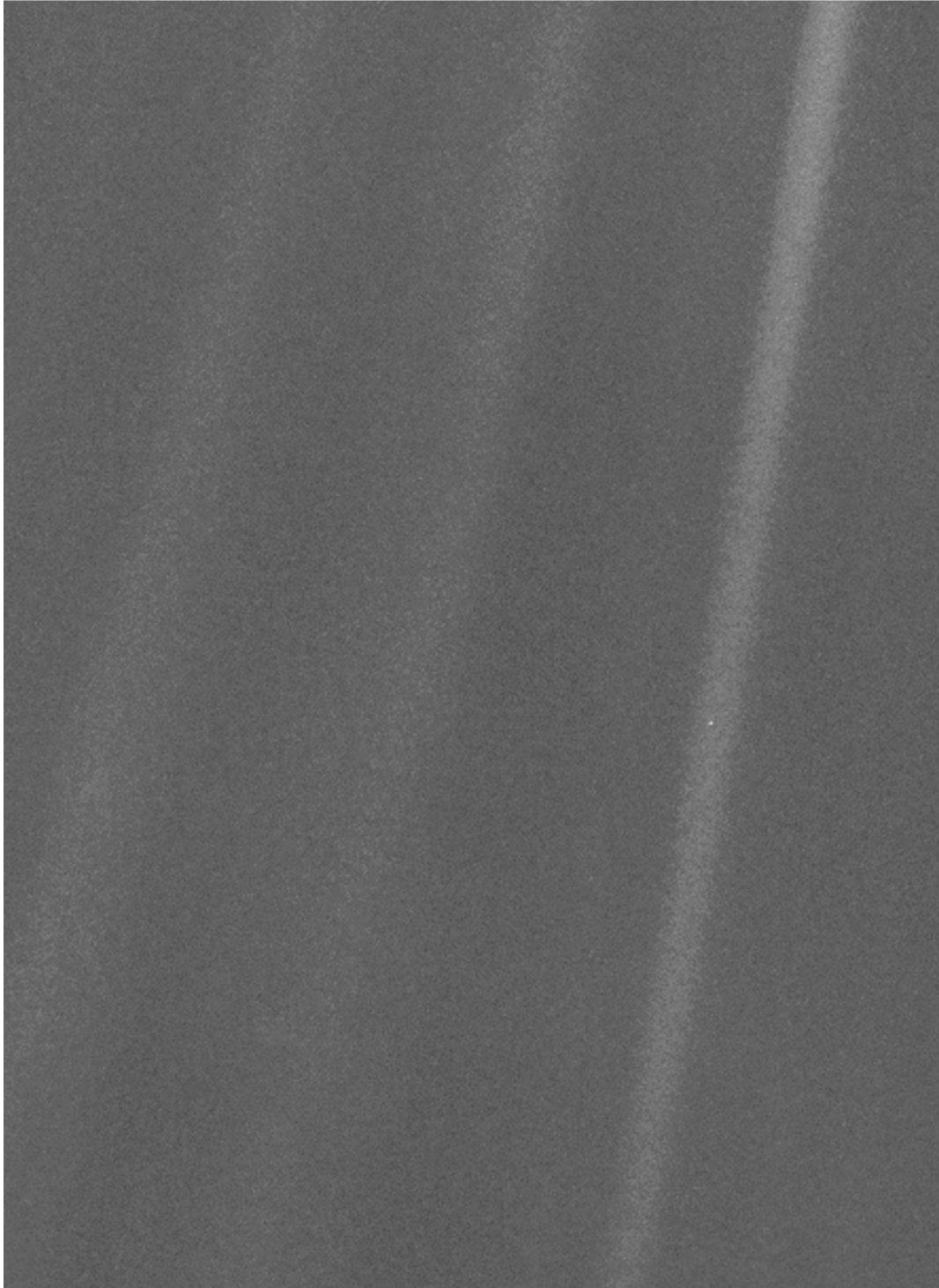


After watching a lecture on the grandeur of the Universe, hearing about the light years between the billions of galaxies and the speed of expansion, with everything getting further and further apart, that sense of tiny speck-ness can be palpable. You don’t have to travel far from the Earth’s surface for human beings to become indistinguishable from the rivers, rocks and sea, and a little further away, you’ll find there’s no visible trace of the civilisation that glows and pulses as we walk through it.

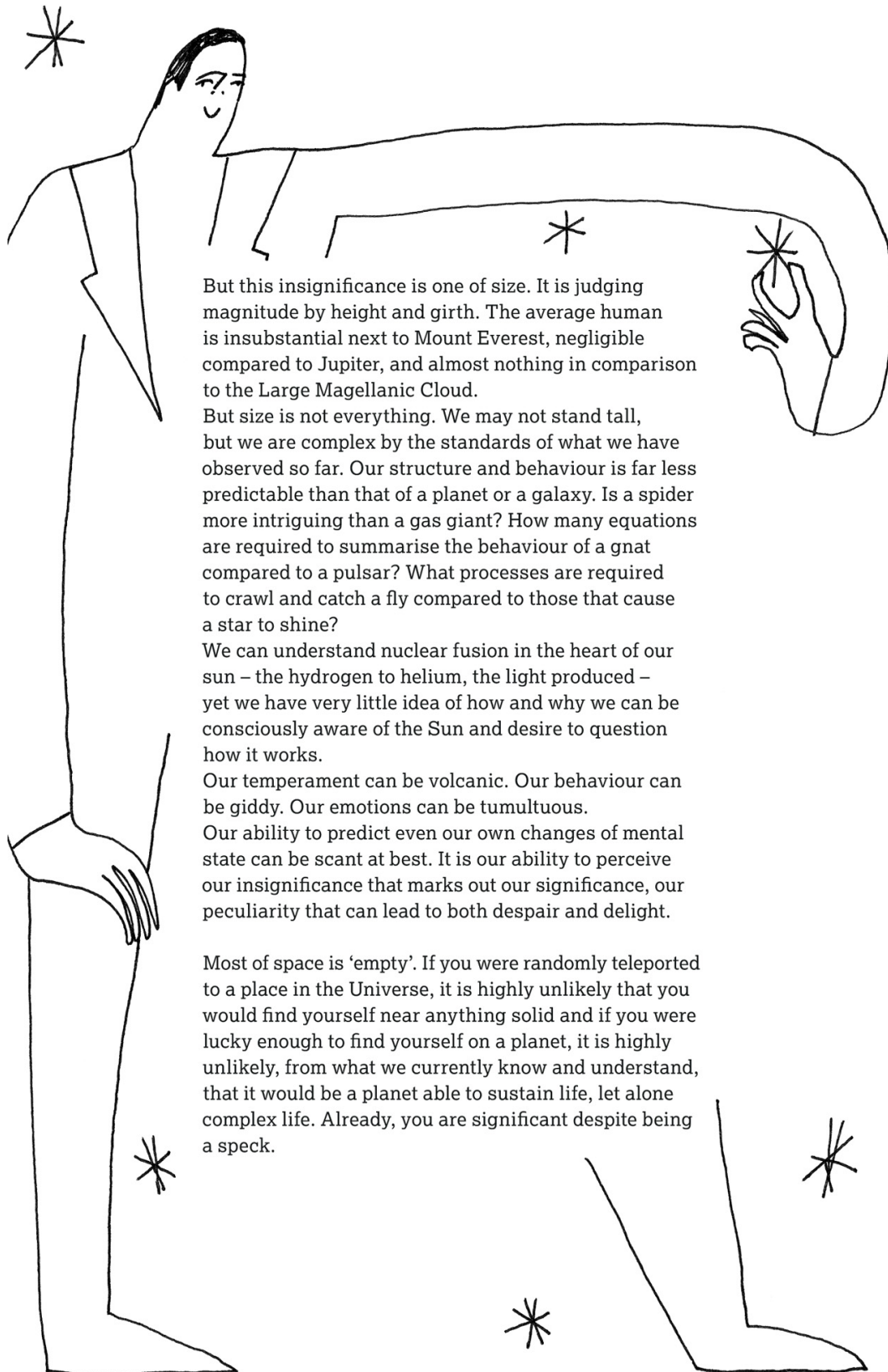


As Voyager’s image of our planet as a ‘pale blue dot’, taken from the parochial proximity of Neptune, shows, you don’t have to travel a great

distance for our home to look like nothing much at all.



The Pale Blue Dot, taken by Voyager 1 on Valentine's Day, 1990, 6 billion kilometres from home.



But this insignificance is one of size. It is judging magnitude by height and girth. The average human is insubstantial next to Mount Everest, negligible compared to Jupiter, and almost nothing in comparison to the Large Magellanic Cloud.

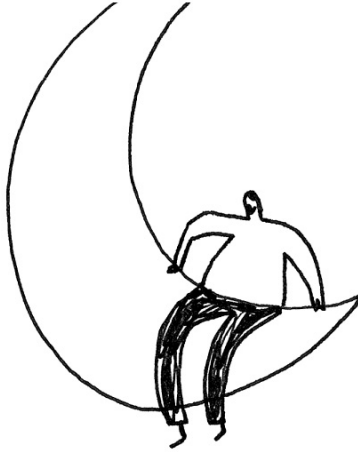
But size is not everything. We may not stand tall, but we are complex by the standards of what we have observed so far. Our structure and behaviour is far less predictable than that of a planet or a galaxy. Is a spider more intriguing than a gas giant? How many equations are required to summarise the behaviour of a gnat compared to a pulsar? What processes are required to crawl and catch a fly compared to those that cause a star to shine?

We can understand nuclear fusion in the heart of our sun – the hydrogen to helium, the light produced – yet we have very little idea of how and why we can be consciously aware of the Sun and desire to question how it works.

Our temperament can be volcanic. Our behaviour can be giddy. Our emotions can be tumultuous.

Our ability to predict even our own changes of mental state can be scant at best. It is our ability to perceive our insignificance that marks out our significance, our peculiarity that can lead to both despair and delight.

Most of space is 'empty'. If you were randomly teleported to a place in the Universe, it is highly unlikely that you would find yourself near anything solid and if you were lucky enough to find yourself on a planet, it is highly unlikely, from what we currently know and understand, that it would be a planet able to sustain life, let alone complex life. Already, you are significant despite being a speck.



Added to the complexity of your structure, even by Earth's standards, your brain is complex and questioning. This may not be an ultimate advantage. It could be this very complexity that spells out your doom. You may be a creature so complex by the standards of the Cosmos that you are driven mad by this complexity. This ability to change your environment, to build and to destroy, to play around with matter at a subatomic scale, could be the making of you and the undoing of you.

Your significance may create and it may destroy.

There may be nothing else out there that will ever know that there was something that once thought and created colliders, and lasers and fibre-optic cables, and tried to find out how the Universe began and how it might end. Or other parts of the Universe may be teeming with life that would consider us as primitive as we consider a maggot.

You may be small, but you are unusual, and you know it, and there's nothing else in this solar system beyond Earth that could say that, or say anything at all.

Every human, therefore, is a thing of great significance in a restricted but important sense. On a cosmic scale, our physical presence is of no consequence. We are temporary assemblies of ten billion billion billion atoms, and in a century or less they will all be returned for recycling. But for the briefest of moments these atoms are able to contemplate themselves.

They will spend an eternity in darkness when we are gone. Our purpose should be to extend their moment in the light as best we can.

PHYSICS BRAIN

An examination



Robin writes:

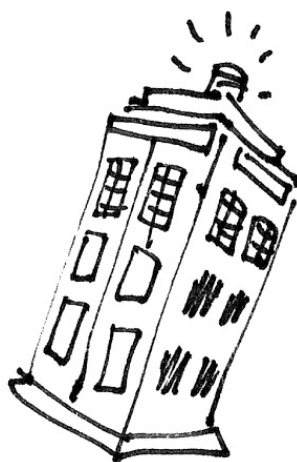
The following piece is predominantly made up of anecdotal evidence, but I am currently working on a series of experiments to examine those neural connections in particle physicists that cannot be made.

From my experience with particle physicists, I have begun to note that in order to have a deep understanding of the structure of our universe, you may have to sacrifice other, more mundane skills, such as the ability to choose what socks to wear, how to make tea and cross the road effectively all the way to the other side.

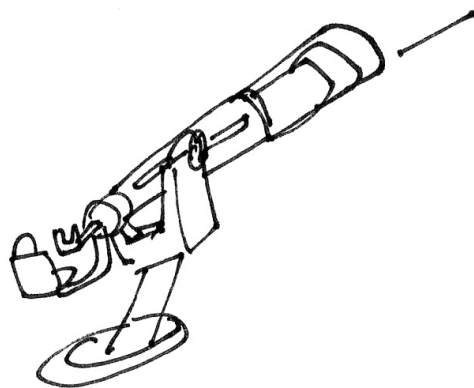
One day, we were standing in the middle of the Lovell Telescope. It was a good day, not only were we at Jodrell Bank, but the science news was that gravitational waves had been detected.

We were ascending the ladders of the Lovell Telescope for a radio documentary about the General Theory of Relativity. We probably didn't really need to, but we wanted to. If you ever get the chance to stand in the

middle of a radio telescope, say yes. I first knew of the Lovell Telescope from watching *Doctor Who* – it was the final Tom Baker story, Logopolis. I'd also seen the telescope plenty of times as set dressing during BBC's *Stargazing*, with Dara Ó Briain standing next to it saying, 'sadly, there is quite a lot of cloud cover tonight, but behind the water vapour there should be lots of stars.'



When the telescope came into view, I experienced the same tongue-tied awe that I experienced when I saw the Grand Canyon for the first time. The lift took us to the walkway under the dish. Crossing to the final ladder, the previous dish, now decaying, surrounds you. This was where the first glimmers of psychogeography sparked. What information had this defunct dish, now shielded from the sky by the dish above it, collected in the previous century?



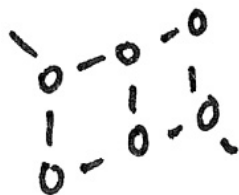
Climbing up what seems like little more than a stepladder, you are suddenly in a beautiful white, circular expanse. Brian had been up there before,

including once for the shooting of a D:ream pop promo, but his trademark delight is not reserved for the TV cameras alone.

Our smiles are beatific. We climb a little up the side of the dish, the curvature creates an illusion that conceals the increasing steepness. The sky almost matches the colour of the dish. We look up and think of the data collected in this bowl. An Arctic-white steel structure in the middle of meadows should feel cold, but it doesn't.

Here is the gatherer of radio waves emitted by astronomical objects. Here is the where signals of the metal-nosed Tycho Brahe's supernova were picked up. This is the place that tracked Luna 2 to the Moon. This is where quasars were defined and pulsars observed. This is not psychogeography, this is psychoastronomy. Carl Sagan stated that astronomy was a humbling occupation, and never have I felt that more fiercely than in the near silence of the Lovell Telescope. Like some psychosomatic sense of feeling all those neutrinos passing through you, your imagination fabricates this same sensation of signals coming from beyond our galaxy.

Back in the café, I ask Brian about gravitational waves. Here is another great day proving the frequent necessity of delayed gratification when it comes to physics. Sometimes a good idea needs to wait for the technology to be created to test it. This story starts with two black holes merging. As they merged, briefly there is a power output five hundred times greater than all the stars in the known universe. Lasers have detected the waves.



Here is the gatherer of radio waves emitted by astronomical objects.

**This is where quasars were defined
and pulsars observed.**

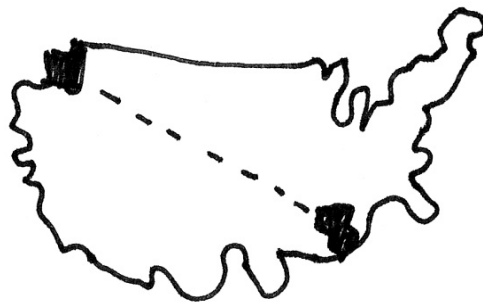
**This is not psychogeography, this is
psychoastronomy.**



Brian explained it like this.

Brian: 1.3 billion years ago a storm in space and time was generated by the collision of two black holes. One of the black holes was 29 times the mass of our sun, the other 36 times more massive. The event lasted for less than two-tenths of a second, during which time the black holes accelerated from

a closing speed of one-third of the speed of light to two-thirds of the speed of light before colliding and merging. Energy was lost to the system in the collision and the storm carried it away at the speed of light. For a tiny fraction of a second, the peak power output exceeded the power output of the entire observable Universe by a factor of fifty. 1.3 billion light years away on a small planet around a yellow star, salt water oceans were populated by single-celled organisms. As the spacetime storm approached, some of these single-celled creatures became organised into collaborative multi-cellular groups, colonised the land, learnt how to do science and built two giant laser facilities with 4km-long arms at right angles to each other at each end of a country called the United States. They switched on the lasers, which they called LIGO and had just upgraded, on 12 September 2015, and two days later at 5.51 a.m. Eastern Standard Time on 14 September 2015, the storm passed through the Earth, changing the effective length of the arms of the detectors by one-thousandth of the diameter of a proton. The signal, described in the box below, was exactly as predicted by Einstein's Theory of General Relativity, first published a century before when nobody knew about black holes or lasers. Life can achieve a great deal in 1.3 billion years.



Some thirty minutes later, Brian finished the story, or at least came to the point of the story where we were now at, because the story continues with each new discovery. He leaned back in his chair, reached for the hot pie that had been brought to him, bit into it, and let out a yelp.



‘Ow, it’s scorching.’

He huffed, puffed and reached for his water, in obvious tongue-blistering discomfort. And I thought that there was something rather beautiful about that. Here is a human who can have a deep understanding of the nature of our universe, yet no understanding of the speed of the cooling of a pie.

While touring, barely a week went by without Brian burning his mouth on some hot food. I would try to train him.

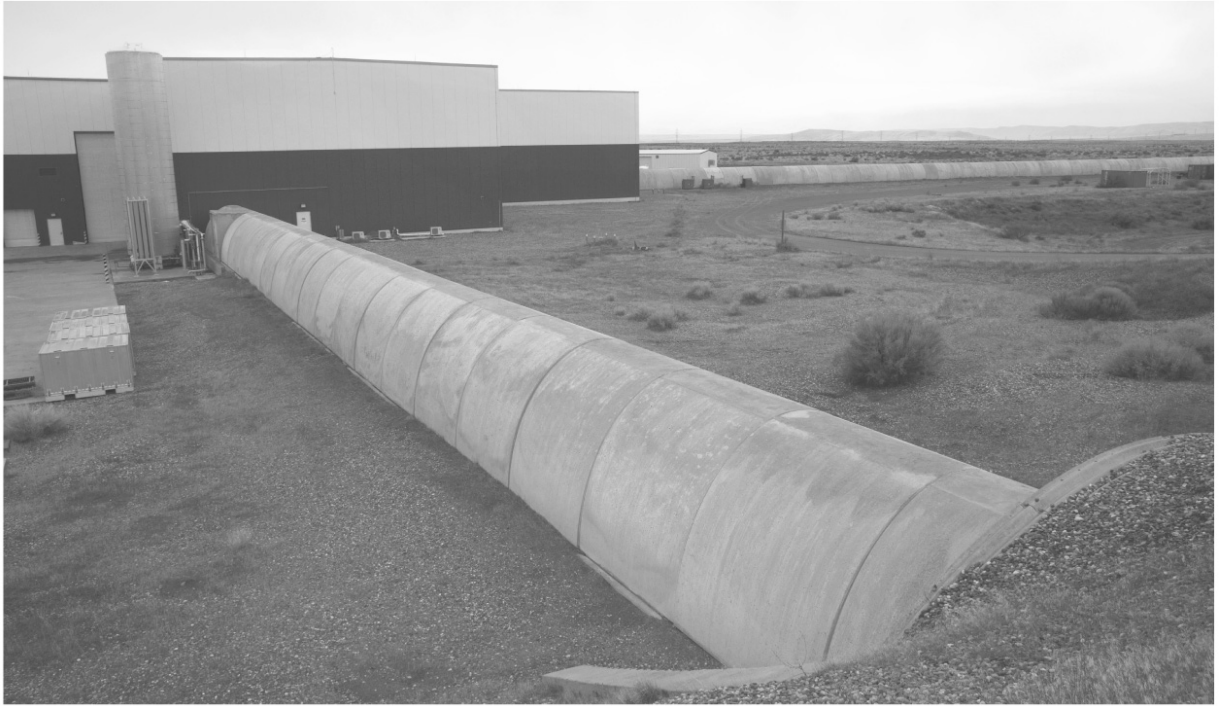
‘Chips, hot.’

‘Hot chips,’ he would smile, before singeing his lips again.

‘Remember what happened last time with the hot chips.’

‘Hot chips,’ he would smile again, then screech as his tongue swelled.

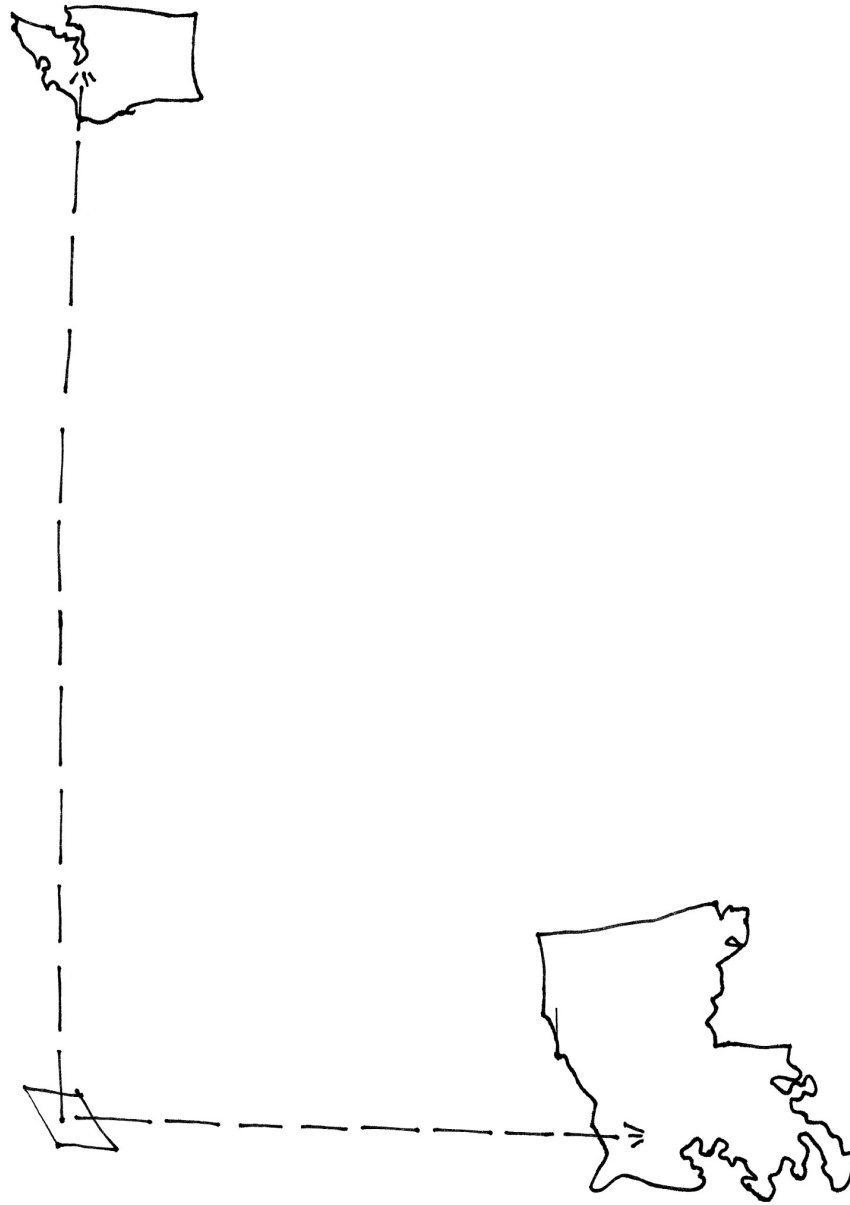
Finally, I realised, there was nothing to be done. The small area of space where my brain had a series of connections to remind me that food sometimes needed to be cooled before it could be consumed had been used up by Brian to comprehend quantum entanglement. That was my tragedy. That was his tragedy. He would continue to burn himself on pie filling, but I would never truly understand how two photons could interact from a distance.



The LIGO Hanford Observatory in Washington State.



The LIGO Livingston Observatory in Louisiana.



The LIGO Experiment

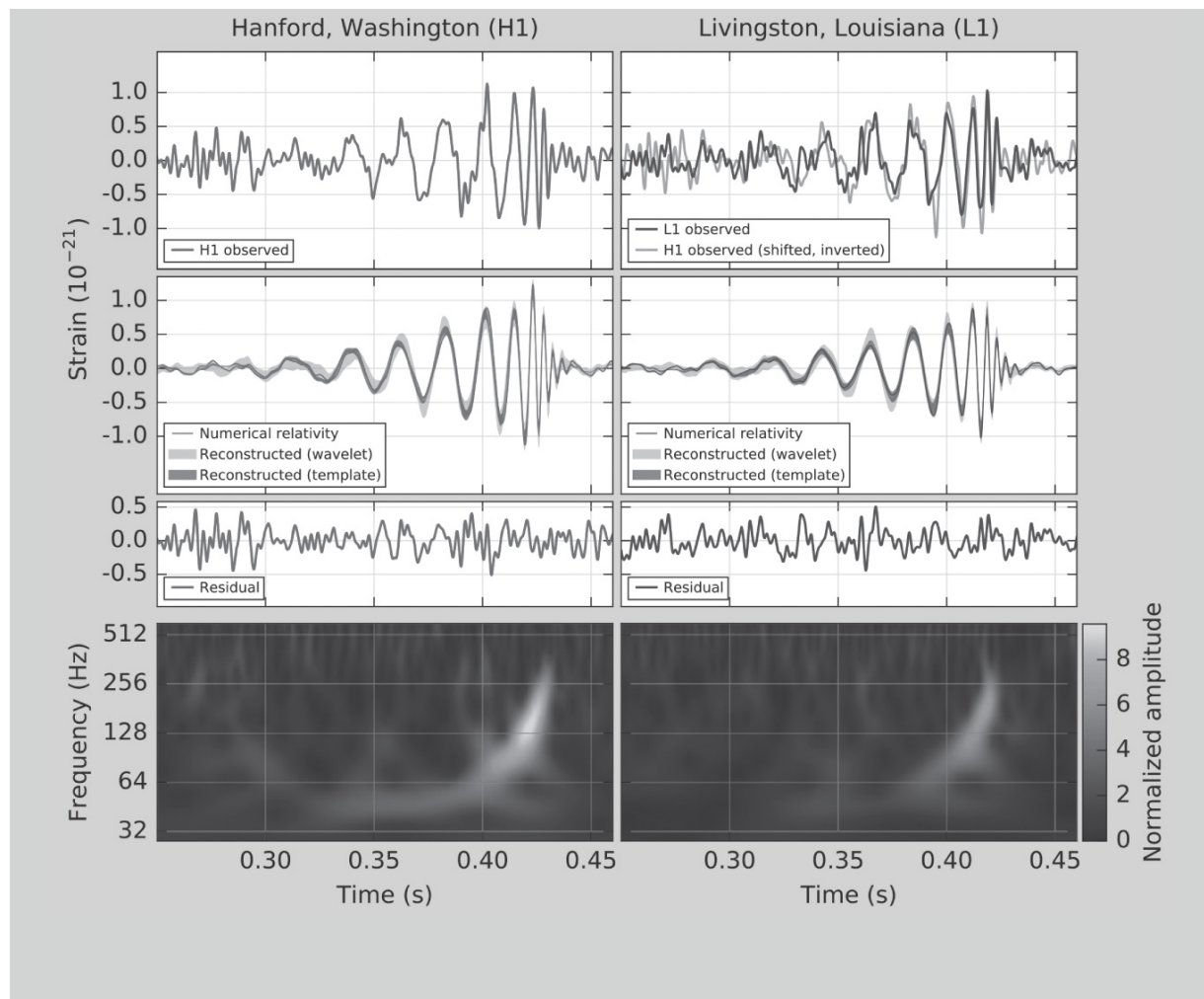
The LIGO experiment consists of two devices known as laser interferometers. One is situated on the north-western seaboard of the US in Washington State, the other in the south east in Louisiana. Each arm consists of a 4-kilometre-long vacuum tube with heavy mirrors suspended at each end and a high-intensity laser beam bouncing between them. As a gravitational wave passes through the experiment, it changes the effective distance between the mirrors in a characteristic way predicted by Einstein's Theory of General Relativity. Because the arms are at right angles, the

prediction is that one arm will shrink as the other expands. Using a technique called laser interferometry, differences in the round-trip time of the photons as they bounce between the mirrors can be measured very accurately. The extreme precision, which is equivalent to measuring the distance to our nearest star to our solar system, Proxima Centauri, to less than the width of a human hair, is achieved by averaging the measurements over the very large number of photons in each high-intensity laser beam. Gravitational waves pass through the Earth at the speed of light, and because the two LIGO sites are separated by 3002 kilometres, an identical signal would be expected in both interferometers, with a time-delay equal to the light travel time between them, if the vibrations of the mirrors have an astrophysical origin.

The collision of two black holes, as imaged by LIGO

The upper left-hand graph shows the results from the Hanford Observatory, and the upper right-hand graph shows the results from the Livingston Observatory. Also shown on the right-hand graph is the signal measured at Hanford (labelled H1), time-shifted by 6.9 milliseconds to account for the light travel time between the detectors and superimposed on the Livingston signal (L1). The signals are clearly very similar, as would be expected if they originated from the same distant astrophysical source and not local noise in either detector. Below the signal graphs there is a comparison between the experimental results and the predictions from General Relativity, given that two black holes of masses 29 and 36 times the mass of the Sun collided 1.3 billion light years away. The bottom two graphs show how the frequency of the gravitational waves and the intensity changed over the 0.15 seconds of the event.

Figure taken from 'Observation of Gravitational Waves from a Binary Black Hole Merger', B. P. Abbott et al., PRL 116, 061102 (2016)



There are (at least!) three remarkable things evident from these pictures. The first is the agreement between the theoretical predictions and the experimental measurements, which are yet another triumph for Einstein's

Theory of General Relativity. The second is the sheer speed and violence of the collision, in which combined masses in excess of 60 times the mass of our star approached, accelerated, collided and merged in the blink of an eye. The third is that we have been able to conceive of and construct an experiment capable of measuring such minute disturbances in the fabric of the Universe: LIGO is a supreme testament to human ingenuity.

AN INTERLUDE

The Recipe for Our Universe

'If you wish to make apple pie from scratch, you must first create the Universe.'

– Carl Sagan

Why is there something rather than nothing? Human beings have come up with quite a few reasons over the centuries. Some believe it starts with one god, occasionally eight, quite a few add that it all rose out of the lifeless waters of chaos. Some gods created humanity because they seemed bored, lonely or playful. Some got it right on the first attempt, others had to give it a few goes. The Mayan gods tried making humans out of mud, then wood, and finally resolved that maize was best. Sometimes the Universe is grown from seeds, sometimes an egg is involved, occasionally it is all the fault of a water beetle.

Creation myths are an often-delightful example of a powerful primordial facet of human nature; when we lack the evidence, resources or knowledge to approach a profound question, we often seek solace in imagination alone.

In the last few centuries our understanding of how our universe works has increased exponentially, but we still don't know why that is. Can something really come from nothing? And not just a little something; the Universe is considerably more than a dove from a magician's top hat. With a little wherewithal, you can work out where the magician hides the dove, but the trick of concealing trillions of galaxies is proving a little more difficult to fathom. It is a subject that has repeatedly come up on *Monkey Cage*.

What happened at the origin of the Universe?

What are the fundamental building blocks of reality?

How did the magnificence of the night sky come to be?

The first thing to emphasise in such discussions is that we don't know how the Universe began and we don't know what the fundamental building blocks are. Just because we don't have an answer doesn't mean there isn't much to talk about, but we might posit the zeroth law of the Monkey Cage, which states that anybody who is certain that they know how the Universe began is not eligible for a place in the Monkey Cage. They usually bring too many robes and torches. Scientists have, however, pushed the frontier of understanding back 13.8 billion years to a time long before the first stars

and galaxies formed, before atoms and atomic nuclei, and possibly before the Hot Big Bang itself.

ROBIN'S WARNING (*added after reading the first draft of this chapter*): This is the hard bit of the book. You may need a pencil to underline sections or just to occasionally jab into your leg or skull as you ask 'but what does it all mean?' Don't let this put you off, but if you are keeping this book in your loo, it will be this chapter that gets people asking, 'why have they been in there so long?'

As they bang on the door, you'll be understanding the Big Bang, or as near as we have got so far to understanding it. Take the advice of Richard Feynman: Read until incomprehension, then start again, and each time you should get a little further.

The observable Universe is the part of the Universe that we can see, and therefore the part that we know with certainty to exist. It is the region surrounding the Earth from which light has been able to reach us in 13.8 billion years. According to the latest estimates, there are around 2 trillion (2,000,000,000,000) galaxies in the observable Universe.

Robin: This means I would make a hasty calculation and say, 'ah, the Universe is 27.6 billion light years across.'

Brian: And you would be wrong.

R: Which is fortunate as it means we still need two presenters for the show. Once I get things right, that's when you should worry.

B: I'm not that worried.

*R: And you are right not to be.
Why isn't it 27.6 billion years across?*

If the question is what happened before the Big Bang, the answer is I don't know

– Professor Carlos Frenk, Series 10, Episode 5 (4 August 2014)

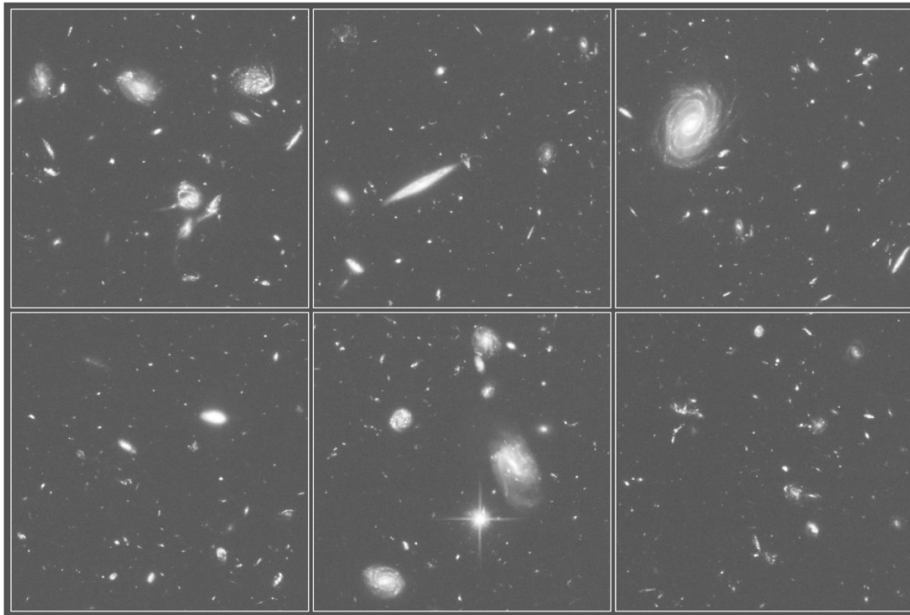
The observable Universe is larger than 27.6 billion light years across because the Universe has been expanding during the time that the light from distant galaxies has been travelling towards us. Einstein's Theory of General Relativity is the theoretical framework we use to understand how the Universe has expanded from the Big Bang to the present day. According to General Relativity, space isn't just a giant box within which things happen, and time isn't just something that ticks along. Rather, space and time are woven together into a 'fabric' called spacetime. The fabric is a dynamic thing; it can stretch and shrink, warp and distort. General Relativity tells us how this happens in response to the matter and energy contained within it, and how in turn matter and energy are affected by the fabric. The famous physicist John Archibald Wheeler had a catchy way of explaining General Relativity; matter tells spacetime how to curve and spacetime tells matter how to move.

The warping of the fabric of the Universe in the vicinity of a star or planet, or indeed any object, is the origin of the force of gravity. The orbit of the Moon, for example, is explained as the response of the Moon to the distortion of spacetime caused by the Earth. You might have seen pictures of the Earth distorting a rubber sheet and the Moon rolling around in orbit like a marble. The important point for cosmology is that space isn't only warped by the presence of matter and energy; it can also stretch or contract in response to its contents. Under certain assumptions, the theory reduces to a simple equation known as the Friedmann Equation, which relates the expansion rate of the Universe directly to the density of matter and energy within it. We explore this relationship in more detail see [here](#).

Now imagine light travelling across space and into our telescopes from a galaxy close to the edge of the observable Universe. The light has travelled for 10 billion years, but space has been stretching during this time – this is what is meant by the statement 'we live in an expanding Universe'. The

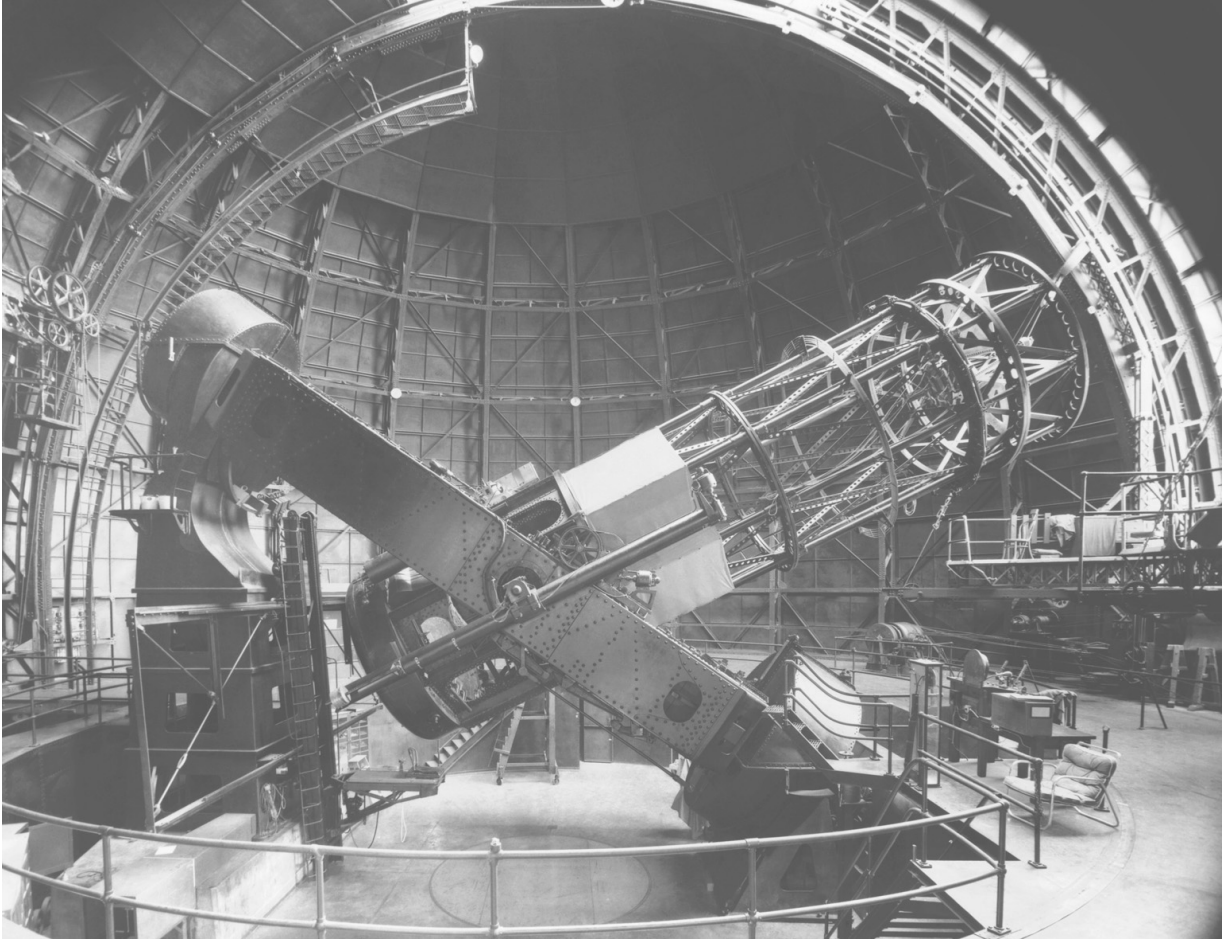
stretch of space stretches the light, which increases its wavelength. This is known as the cosmological redshift, because longer wavelength light is redder.

We can measure the redshift for any given galaxy, and if we repeat this for many different galaxies at different distances, we can map out the rate of expansion of the Universe throughout its history. These measurements can be used to calculate the size of the observable Universe: We are asking the question ‘how far away are the most distant galaxies *now*, given that they have been receding from us at some (varying) rate during the time it has taken the light emitted from them to travel to us?’



The Hubble Ultra Deep Field image. This is a long-exposure photograph of a piece of sky approximately one-tenth of the diameter of the full Moon taken by the Hubble Space Telescope. It contains over 10,000 galaxies. Images like this allow astronomers to estimate the number of galaxies visible across the entire sky.

The answer is that the most distant objects we can see are around 46.5 billion light years away now, and the observable Universe is therefore 93 billion light years in diameter.



The Mount Wilson Hooker Telescope was built in 1917. Many important advances in astronomy took place here, including Hubble's pioneering observation of the redshift of distant galaxies.

The number of galaxies within this 93-billion-light-year region gives us a feel for the size of the Universe, because galaxies are vast structures in their own right. Our home galaxy, the Milky Way, contains around 200 billion stars, give or take a factor of 2, and it takes light around 130,000 years, travelling at 300,000 km/s, to cross it. Many of the stars have solar systems with moons and planets, and on a human scale even planets are big. It is impossible to truly comprehend the scale of what's out there, and most professional astronomers don't even try, but this does not prevent us from understanding a great deal about how it came into existence.

R: I am always intrigued by what goes on in your brain when comprehending such big numbers. These are the times I get cosmological

vertigo. If I stand at the seashore on a clear night and stare at the sky until as many stars as possible come into focus, there is a moment when my mind seems to shudder and pause. It's as if it almost gets to comprehend the enormity, but is then so assailed by the size of it all that it considers the best option is to shut down and attempt to reboot.

The finite speed of light is a gift, because when we observe galaxies we are also looking back in time. The light from the most distant galaxies we can see has travelled for over 13 billion years to reach us. This means we are observing them shortly after they formed. The next generation of telescopes, including the James Webb Space Telescope and the Square Kilometre Array radio telescope under construction in Australia and South Africa, will allow us to observe the formation of the first stars and galaxies when the Universe was only a few hundred million years old.

Distant galaxies are not the oldest structures in the Universe that we can observe directly. During the first few hundred thousand years after the Big Bang, the Universe was so hot that even atoms couldn't form. All of space was filled with a hot, dense soup of hydrogen and helium nuclei and electrons. There was plenty of light around in these early times – the Universe was in some ways like a giant glowing star – but the light didn't get very far. This hot soup is known as a plasma, and it is opaque to light because the photons keep bumping into the densely distributed electrically charged particles.

As the Universe continued to expand the temperature fell to around 3000 degrees Celsius, 380,000 years after the Big Bang. This is cool enough for electrons to be captured by the positively charged nuclei, and so the first atoms formed. At this moment in cosmic time, the Universe became transparent and the light emitted from the glowing hot gas of newly minted atoms has travelled through the Universe in straight lines ever since. Some of this light is reaching the Earth today, and we have built detectors to capture it, enabling us to photograph the ancient plasma (see [here](#)). The light is stretched by a factor of just over a thousand due to the expansion of the Universe, which means it is no longer visible to our eyes. Instead, it is in the microwave and radio part of the spectrum, and is known as the Cosmic Microwave Background Radiation, or CMB.

Occasionally we get letters on *The Infinite Monkey Cage* from listeners who take a sceptical view of modern science,^{[1](#)} and some of them like to

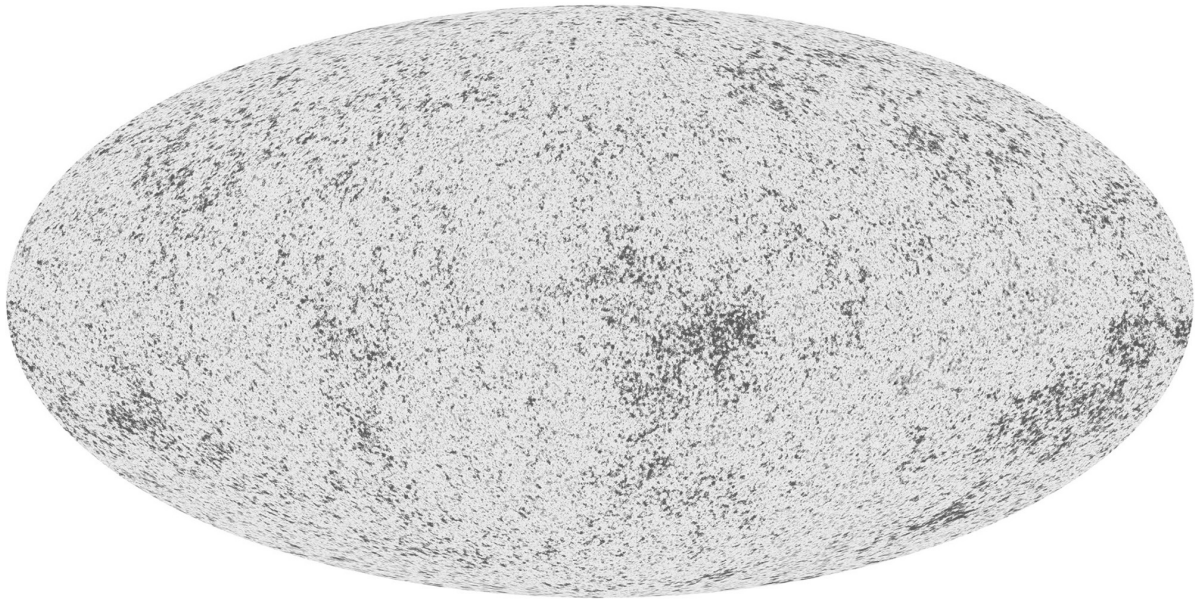
challenge ideas such as the Big Bang.

R: Before we even open a letter, we can always know if it is one taking cosmology to task from the simple clue that it is a letter. Letters for fury, emails for compliments. Occasionally letter writing is used for lengthy descriptions of a new theory of the Universe, but we can recognise Jim Al-Khalili's handwriting now, so we just return to sender, which is quite easy, as he is only three desks away.

The answer to someone who disagrees with the statement that there was a hot, dense phase in the early history of the Universe shortly after the Big Bang is to draw their attention to this photograph (below) and point out that we can actually see it. The CMB was discovered in 1964 by Arno Penzias and Robert Wilson, and from then on it was not possible to argue that stars, planets and galaxies have existed forever, because we can observe the Universe at a time when there were none.

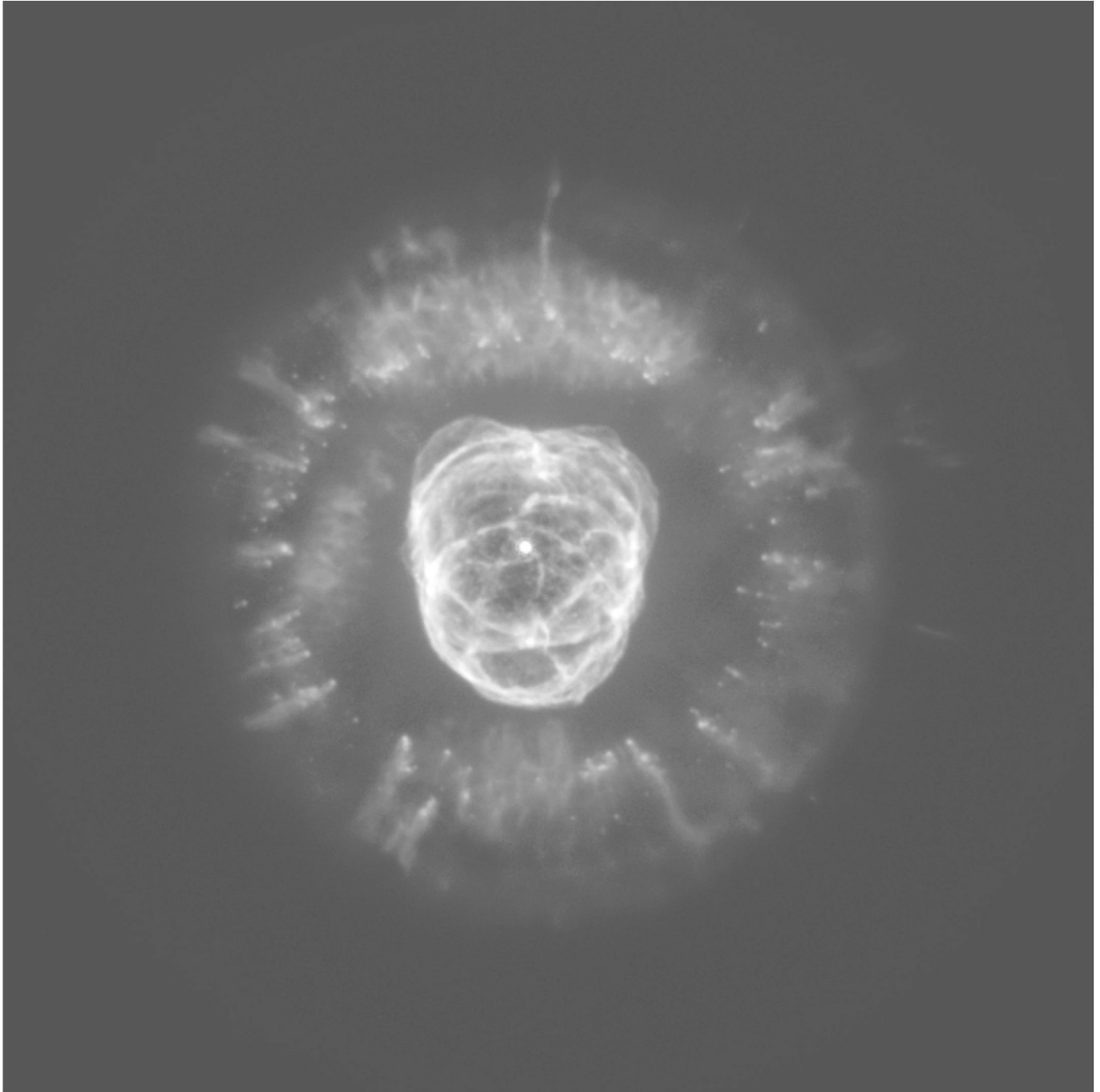
The colours in the photograph of the CMB correspond to areas of very slightly different density in the young Universe, which manifest themselves as areas of different temperature on the sky. The over-dense regions of gas ultimately collapsed under the influence of gravity, and in so doing the cosmic dark ages ended with the ignition of the first stars and the formation of the first galaxies.

This might seem as far as we can go in understanding the early Universe, because we can't see further back in time than the CMB, but we can do more by employing some well-understood physics from other fields. If we follow the timeline of the Universe backwards from the release of the CMB, 380,000 years after the Big Bang, we expect conditions to get hotter and hotter. When temperatures reach a billion degrees or so, atomic nuclei fall apart, just as atoms fall apart at temperatures of a few thousand degrees. If the Big Bang model is correct, such conditions would have been present during the first few minutes in the life of the Universe, and we understand these conditions very well because we can create them in laboratories on Earth.



The Cosmic Microwave Background Radiation as photographed by the European Space Agency's Planck Satellite. This image, of the entire sky, is a picture of our universe as it was 380,000 years after the Big Bang.

Atomic nuclei are assembled out of two smaller constituents known as protons and neutrons. The number of protons in the nucleus determines the chemistry of the atom, and this is how we label the chemical elements. Hydrogen is the simplest element, with a single proton in the nucleus. Helium is the next simplest, with two protons, lithium with three, and so on. The number of neutrons in the nucleus of an element can vary, but this does not affect the chemistry. There is a form of hydrogen called deuterium, with one proton and one neutron in the nucleus. Helium usually has two neutrons, but occasionally one, lithium usually four, but occasionally three.



The Eskimo Planetary Nebula, almost 3000 light years away in the constellation of Gemini. The outer layers of a Sun-like star nearing the end of its life, rich in newly synthesised heavy elements, are dispersed out into space.

Stars like the Sun shine by converting hydrogen into helium in their cores. This process is called nuclear fusion. When stars exhaust their supply of hydrogen, as the Sun will in around 5 billion years' time, they begin to fuse helium into heavier elements such as carbon, oxygen and iron, but this phase does not last long. Ultimately the star dies, jettisoning its outer layers

as a planetary nebula or, for the case of the most massive stars, in a supernova explosion. This stellar debris enriches the dust clouds that will collapse to form new generations of stars and planets, and this is the source of all the elements heavier than lithium in the Universe today. This is the origin of Carl Sagan's famous quote 'We are all made of star stuff'.

Astronomers can measure the relative abundances of the different elements in the Universe by analysing the light from stars and galaxies. The most distant galaxies have a lower fraction of heavy elements, which is to be expected because we are seeing them when the Universe was young and there had been less time for stars to construct them. But even the youngest stars and galaxies are always found to consist of approximately 75 per cent hydrogen and 25 per cent helium, with traces of deuterium and lithium. This was a great puzzle to astronomers, because calculations show that, at most, stellar nuclear fusion can only account for a small fraction of the observed helium in the Universe, and none of the deuterium.

The solution to this problem is known as Big Bang nucleosynthesis; most of the helium and all the deuterium in the Universe was constructed in the first few minutes in the life of the Universe, when conditions were hot enough for nuclear fusion to occur. We can calculate the relative amounts of hydrogen, deuterium, helium and lithium that we should expect to see if we know the density of protons, neutrons and photons in the early Universe and the rate of expansion, which tells us the rate at which the Universe cooled. The calculations employ a significant amount of our understanding of fundamental physics, and the details are a little complicated, so we'll only skim over them here.² The thing to bear in mind is the quite astonishing precision with which we can speak about the Universe as it was during the first 20 minutes or so after the Big Bang.

We are all made of star stuff.

– Carl Sagan

There are four fundamental forces of nature; gravity, the electromagnetic force and the strong and weak nuclear forces. We've already met gravity, as described by Einstein's Theory of General Relativity. The other three forces are described by the Standard Model of particle physics, which we outline see [here](#). The Standard Model allows us to calculate the ratio of protons to neutrons present when nuclear fusion began. This ratio is 6 protons for

every neutron, and was fixed around 3 seconds after the Big Bang. The protons and neutrons are the raw materials for the subsequent period of nuclear fusion which creates helium, deuterium and lithium.

Deuterium synthesis started around 2 minutes after the Big Bang and ceased around 18 minutes later. These numbers are calculated using the Friedmann Equation, which tells us the expansion rate of the Universe and therefore how the temperature falls over time. Before 2 minutes, the density of photons was so high that any deuterium nuclei formed by a proton and a neutron binding together under the influence of the strong nuclear force were rapidly destroyed by the photons. After 20 minutes, the temperature had fallen too far for nuclear fusion to continue. All the neutrons had been swept up into deuterium, and most of the deuterium had been converted to helium. The initial ratio of 6 protons to every 1 neutron leads to a prediction that around 24 per cent of the mass of the atoms in the Universe should be helium, and almost all the rest should be leftover protons in the form of hydrogen. This is precisely what we observe.

This is a great triumph for the Big Bang model. The calculation relies on our understanding of the four fundamental forces of nature encoded in the two great pillars of twentieth-century physics, General Relativity and the Standard Model. It is hard to see how we could get this number correct if there were some serious flaws in our understanding of physics as it applies to the conditions present in the first few minutes in the life of the Universe.

A second triumph is the predicted small amount of leftover deuterium. Astronomical observations of distant bright galaxies known as quasars tell us that there are around 26 deuterium atoms for every million hydrogen atoms in the Universe, all of which must have been produced in Big Bang nucleosynthesis because deuterium is destroyed faster than it is produced in the nuclear reactions inside stars. This theoretical calculation is highly sensitive to the ratio of protons and neutrons to photons during Big Bang nucleosynthesis, which is referred to as the baryon to photon ratio because protons and neutrons are collectively known as baryons. This ratio does not change over time, because the expansion of the Universe dilutes the number of photons and baryons by the same factor; the baryon to photon ratio should be the same today as it was in the first few minutes in the life of the Universe. The calculations agree with observation if the baryon to photon ratio is 6×10^{-10} ; i.e. around 1 baryon for every billion photons.

R: The story of what makes the periodic table is so epic, so immense in its grandeur, that I wonder how it was made so dull when I was taught it at school. It was learning the ingredients of the Universe by rote, rather than learning how Mendeleev constructed it in the way he did and why. The thirteen-year-old me would never have imagined that the 48-year-old me would have a favourite element and be more interested in the periodic table now than I was forced to be then. It is Tellurium, by the way; the element that makes you smell of garlic and is used in solar panels. It is particularly hated by a certain sort of individual because it combines two of their pet hates, renewable energy and foreign food smells. Sorry, I interrupted you...

We know the photon density in the Universe today very precisely from our measurements of the CMB, because it is directly related to the temperature of the CMB; there are 413 photons per cubic centimetre. Together with the baryon to photon ratio which is required by the Big Bang nucleosynthesis calculations to match observations of the deuterium content, this allows us to calculate the average density of baryons in the Universe today. Since these are the building blocks of all planets, stars and galaxies (baryons are far more massive than electrons), this is the average density of normal matter in the Universe today. The number is 0.25 baryons per cubic metre.

We can check this prediction by going out and weighing the Universe, and there are many ways of doing this. The simplest way is to employ the approach that was used historically to weigh the Sun. If you know the radius and the period of a planet's orbit, you can use Isaac Newton's laws and the measured strength of the gravitational force to calculate the mass of the star. In the 1930s, the astronomer Fritz Zwicky calculated the mass of the Coma Cluster of galaxies in this way. Today astronomers employ several methods of weighing the Universe, from looking at the orbits of stars around individual galaxies to observing how galaxy clusters bend the light travelling through them because their great mass distorts the fabric of the Universe (known as gravitational lensing). All methods reveal that there is roughly 1.5 baryons' worth of mass per cubic metre of space, which at first sight would appear to contradict the prediction of 0.25 baryons per cubic metre from Big Bang nucleosynthesis.

R: Ah ha. Not so clever now, eh? Back to the drawing board. I have a theory about a water beetle...

B: Not so fast, comedian.

Astronomers are also able to measure what fraction of the mass in galaxies and galaxy clusters is made up of baryons in the form of stars, gas and dust, by looking at the amount of light emitted from the stars and by detecting radio waves and X-rays emitted from clouds of interstellar gas. They find that only about one-sixth of the observed mass is ‘normal’ baryonic matter. The rest of the mass appears to be dark, and to interact very weakly with the stars, gas and dust. This mysterious stuff is known as dark matter, and current observations are consistent with it being a new kind of particle which did not participate in Big Bang nucleosynthesis because it doesn’t interact strongly with particles like protons, neutrons and photons. A measured mass density of 1.5 baryons’ worth of mass per cubic metre, one-sixth of which is made up of protons and neutrons, is therefore in accord with the Big Bang nucleosynthesis prediction of 0.25 baryons per cubic metre.

Taken together with the measured abundances of hydrogen, helium, deuterium and lithium, these results are a remarkable triumph for the Big Bang model, but they do leave us with the puzzle of the nature of dark matter. There are a host of experiments around the world aimed at either the detection of dark matter, on the rare occasion it bumps into the normal matter of a detector, or the direct production of dark matter particles at accelerators such as the Large Hadron Collider. No signal has been detected at the time of writing, but the experiments have certainly not ruled out the possibility that dark matter is composed of an as-yet-unknown weakly interacting particle, and the search continues.

R: While touring, it is often a delight to find out how terrifyingly smart the youngest members of the audience are. Frequently, parents leave messages saying, ‘still a bit lost on the bit about dark matter, but my 10-year-old is helping me out with it as we queue to leave the car park.’ At the first live event Brian and I did together, a young child, maybe ten years old, was desperate to ask a question. The audience looked on him with smiling, vaguely patronising eyes, expecting a question about

Martians or rainbows. ‘Professor Cox, dark energy, will we ever know what dark energy is or is it merely a scientific idea invented as an alibi for an area of knowledge we can never truly understand?’

‘We are having a bit of trouble with that. Next question please,’ came the reply.³

How are we doing with dark energy?

There is one more constituent of the Universe that was discovered in the mid 1990s – dark energy. By looking at the stretch of the light from distant supernova explosions, two teams of astronomers working independently measured the expansion rate of the Universe and found it to be increasing. The Universe is accelerating! This came as a shock, because everyone had assumed that the expansion rate of the Universe should have been slowing down after the Big Bang due to the gravitational attraction of all the matter and dark matter. General Relativity is able to account for an accelerating expansion through the introduction of something called the cosmological constant. Einstein initially introduced it because he could do so mathematically, and he thought a cosmological constant would allow him to balance the tendency of a matter-dominated Universe to slow down in its expansion, and thereby create a stable, eternal Universe. This isn’t possible, and Einstein subsequently removed it and referred to the attempt as his biggest blunder. The cosmological constant is a sort of energy, and just like matter and dark matter, it must be included in the calculation of the average energy density of the Universe.⁴ The amount of energy required to produce the observed acceleration in the expansion rate (recall that these are related via the Friedmann Equation) is equivalent to 3.5 baryons’ worth per cubic metre.

We now have our inventory of the Universe. There are 0.25 baryons (protons and neutrons) per cubic metre, 1.25 dark matter particles per cubic metre, and 3.5 baryons’ worth of dark energy per cubic metre, adding up to a total matter and energy content of the Universe of 5 baryons’ worth per cubic metre today. These results were arrived at from a combination of independent observations by many different groups of astronomers over almost a century, and our understanding of basic physics.

At this point, a sceptical reader – the only sort of reader we expect for an *Infinite Monkey Cage* book – may object that these measurements might be

Looking at the photograph of the CMB see [here](#), we see that there is a lot of detail. The afterglow of the Big Bang is not uniform; some regions of the sky are at a slightly different temperature to others, and these variations in temperature correspond to regions of different density in the young Universe. The differences are very tiny – 10 millionths of a degree – which is why they weren't detected until NASA's high-precision COBE Satellite began taking data in 1989. Until then, the CMB appeared to be a perfectly uniform glow across the sky. These tiny fluctuations are a gold-mine for

cosmologists, because they are a window onto the Big Bang. In 2006 George Smoot and John Mather received the Nobel Prize in Physics for their discovery.

There are times when, even for a professional physicist, it is appropriate to celebrate the astonishing power of theoretical physics. As we wrote at the beginning of this chapter, the question of the origin of the Universe is an ancient one, spanning the history of human thought. The motivation for a creation story may have been the vital beauty of the River Nile, the clockwork motions of the Sun and stars or the very existence of verdant land adrift on limitless oceans. The fluctuations in the CMB may not be as romantic, but the explanation of their origin is part of a creation story with a difference. This one is a scientific creation story, which means it makes predictions which can be checked by observation. The theory is called Inflation, and it includes a mechanism for seeding the density fluctuations in the CMB, which in turn can be used to cross-check the relative amounts of matter, dark matter and dark energy in the Universe. It also suggests why we observe the energy density of the Universe to be 5 baryons per cubic metre. And for good measure, it explains the Big Bang.

The basic idea of Inflation is that before the Universe was hot and densely packed with matter and radiation, it was still in existence but in a very different state. It was cold and empty, except for something known as the inflaton field. Picture the inflaton field as a still ocean of energy filling all of space. The effect of the inflaton field was to make the Universe expand very fast, like a super-charged cosmological constant. Any given patch of space was doubling in size every 10^{-37} seconds.⁵ Let's focus on a small patch a billion times smaller than a proton. After 10^{-35} seconds this patch had grown to the size of a melon, at which point inflation stopped. The energy in the field didn't disappear; it was transformed into a high-temperature soup of particles – ultimately the building blocks of the protons and neutrons and the dark matter particles that we see in the Universe today. This is what we call the Big Bang. In this sense, inflation happened before the Big Bang. Cosmologists now refer to the heating of the Universe at the end of inflation as the Hot Big Bang, to differentiate it from the beginning of inflation. The reason we are interested in this particular melon-sized patch of space at the Big Bang is that it was destined, over the next 13.8 billion years, to grow into our observable Universe. It contained the energy to make all the stars in two trillion galaxies, plus all the dust and gas and

dark matter. This is why the word 'Hot' is appropriate. The conditions in those early times are unimaginable, but not beyond the reach of our current physical theories.

This is certainly not to say that our understanding of the origin of the Universe is complete. We know nothing about how inflation began, or even if it began. According to Einstein's Theory of General Relativity, there must have been a beginning, which we might still refer to as the Big Bang. We know that Einstein's theory breaks down at the extreme energies present in the very earliest times, however, but we do not have the Quantum Theory of Gravity that we suspect must replace it. Without this, it is difficult to say anything with confidence about the origin of the Universe, or even address the question of whether there had to be an origin. Our ability to make concrete predictions stops during inflation when the observable Universe was a billion times smaller than a proton, which is why we began our description at that point.

R: This is the point where I can understand why people might prefer a Creation Myth involving a water beetle or some gods making humans from maize, though those myths don't really answer much, they don't fracture the brain quite so much. To look in a vegetable drawer and know that our universe has been the size of everything in there, however briefly, pea, sprout and cabbage, jars the mind. To think that the whole Universe was once the size of our brain and that our brain can somehow conjure with ideas of such rapid expansion leads to feedback loop that confounds and excites, but not always in that order. I have found it impossible to get a chest of drawers in the back of a Ford Fiesta and a tent back in its bag, so fitting a universe into a melon boggles me and my mind. Mind you, now the Universe has been unpacked, just how easy would it be to put it back again?

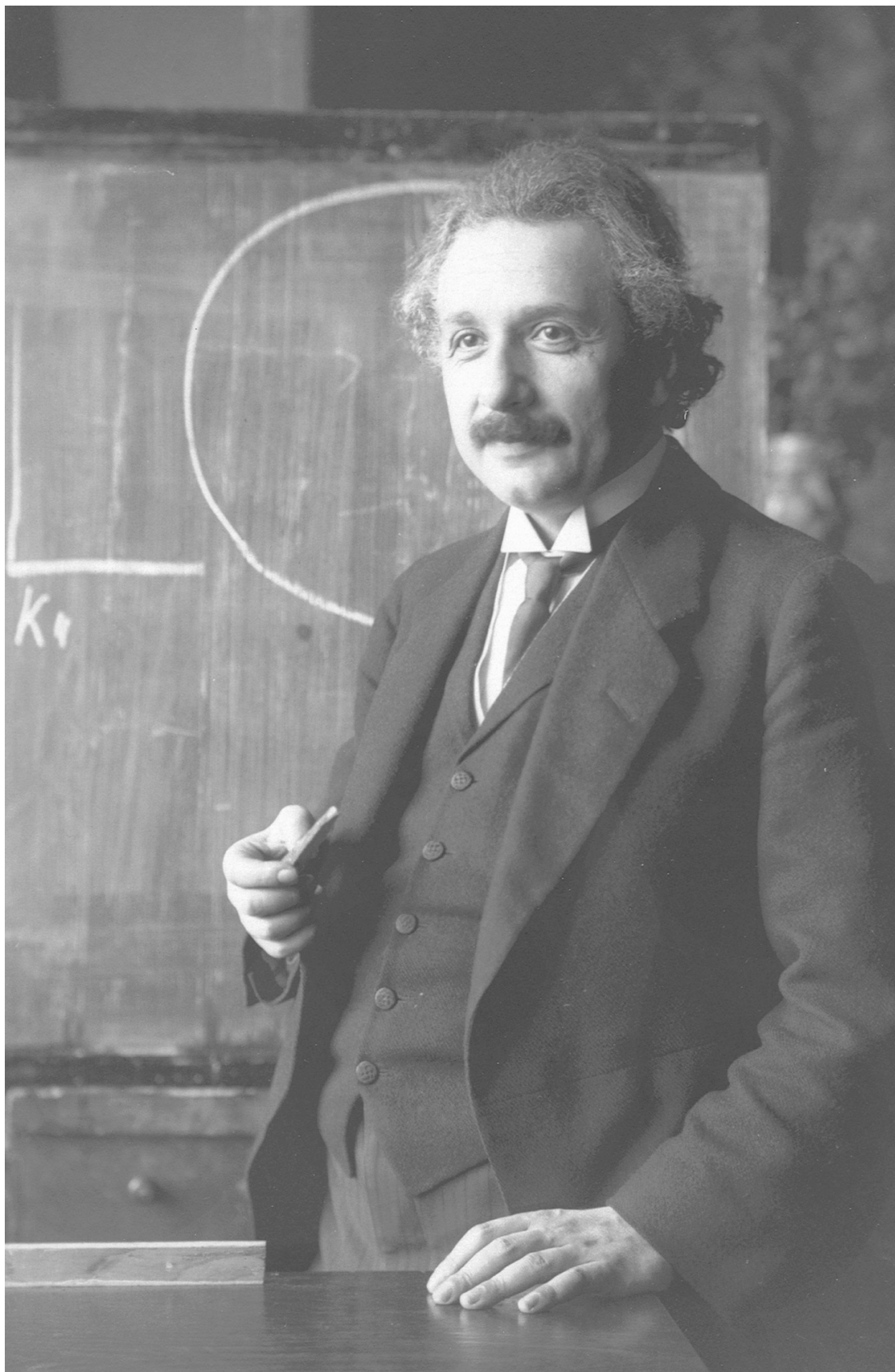
It does all sound quite fantastical, and the theory of Inflation as we've described it so far is no better or worse than any other creation myth because we've just said a lot of things that can be related to the size of things in your vegetable drawer without any apparent motivation. Now for the good bit, because we will describe some predictions of the theory that can be tested.

$$E = mc^2$$

The behaviour of the inflaton field is described by quantum theory, which along with Einstein's Theory of General Relativity is one of the foundations of modern physics; the Standard Model is a quantum theory. We have a very good understanding of quantum theory, which has been tested for over a century, and we trust its predictions. The theory tells us that there is no such thing as a still ocean of energy. Rather, we should think of the inflaton field as a stormy sea. The crests of waves represent regions of higher energy in the field, and the troughs represent regions of lower energy. As inflation draws to a close and we approach the Hot Big Bang, regions of space occupied by wave-crests will continue to expand a little longer than regions populated by troughs, simply because there is more energy there, and it is the energy in the field that is driving the expansion. When inflation ends and the Universe heats up, the over-stretched regions will become slightly less-densely populated with particles than the under-stretched regions. Because we can calculate the size of the waves in the inflaton field using quantum theory, we can also calculate the resulting fluctuations in the density of particles after the Hot Big Bang. Remarkably, the calculations match the observed density fluctuations in the CMB.

This is persuasive for several reasons. Firstly, inflation as a theory was not introduced to explain the density fluctuations in the CMB. The mechanism for the rapid expansion in the form of the inflaton field came later, *after* the idea that a phase of rapid expansion would be able to explain some other features of the observable Universe that we'll describe later in the chapter. Secondly, the prediction of the density fluctuations was made before they were discovered by the COBE Satellite.⁶

Now let's get to the icing on the cake, which comes from thinking about precisely how the under- and over-dense regions in the newly-formed melon-sized sea of elementary particles seeded during inflation led to the patterns we observe in the CMB.



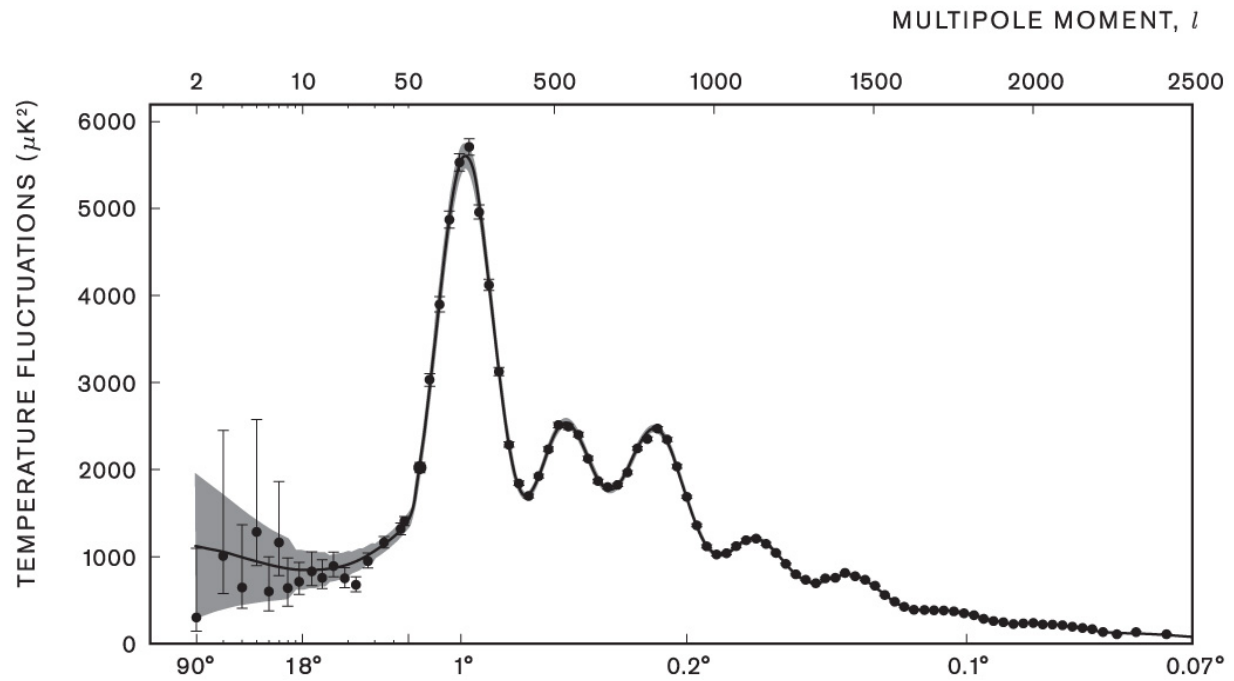
These initial under- and over-dense regions acted as sources for sound waves, which propagated outwards through the hot soup of charged particles and dark matter that filled the Universe for the first 380,000 years after the Hot Big Bang until the CMB was released. You might picture the origin of the Universe as a kicked bucket of water. The kick produces a disturbance in the water which travels as waves on the surface, heading off from the sides of the bucket at a speed determined by the physics of water. The under- and over-dense regions at the end of inflation are like the kick, and the hot soup of particles in the young Universe is like the water. The crucial point is that, just like the water waves in the kicked bucket, the sound waves began their journey through the hot particle soup at the *same time*. This is a very specific prediction of inflation because inflation stopped in an instant. What sort of pattern should this leave in the CMB? Imagine disturbing still water in a (very large) bucket by throwing a handful of pebbles into it such that they all hit the surface at the same time. At some later time you will see a series of interlocking circles and, because the pebbles hit the surface at the same time, the radius of all the water-wave circles will be the same. The prediction from inflation looks like this, although the waves in the plasma of the young Universe will be spheres of equal radius rather than circles. The radius of the spheres when the CMB is released 380,000 years after the initial disturbance will depend on the speed of the waves through the soup of particles. This depends on what the soup is made of; the relative numbers of the different kinds of particles and the way the particles interact with each other. We should see these interlocking spheres today frozen into the CMB, although they will look much bigger on the sky because the light from them has travelled through the expanding Universe for 13.8 billion years. The CMB therefore encodes a vast amount of information about the particles present in the early Universe and its subsequent expansion, which in turn depends on the matter and energy content of the Universe throughout its history.

The graph on the opposite page has been described by *Monkey Cage* panellist Professor Carlos Frenk as one of the most wonderful achievements in the history of human civilisation. It is a mathematical representation of the CMB photograph shown see [here](#). The graph is derived from something known as a two-point correlation function and it allows us to see the effect of all those spherical waves propagating through the hot particle soup of the early Universe and frozen into the CMB when the first atoms formed. The

positions and relative heights of the peaks on the graph contain all the information we want to know. The very existence of peaks means that there were sound waves propagating through the young Universe, and that they all began their journey *at the same time* at the Hot Big Bang, as predicted by inflation. If the spherical waves did not have the same radius when the CMB was released there would be no peaks. The position of the first peak is directly related to the speed of sound in the primordial particle soup, which depends on its constituent particles and their interactions.

The relative heights of the peaks also tell us a great deal. They diminish in size because photons travel only a finite distance through the particle soup before scattering, and this distance is related to the density of electrically charged particles – mainly the hydrogen and helium nuclei and electrons we discussed earlier. The odd-numbered peaks are slightly boosted in size relative to the even-numbered peaks. This effect is related to the damping effect of dark matter particles in the soup, which do not directly support the propagation of the waves because they don't interact with each other or the electrically charged matter particles, but do exert a gravitational influence, which tends to make the oscillations associated with the odd-numbered peaks more intense. This is all complicated and subtle stuff, and we have only scratched the surface, but hopefully you get a sense that the CMB is a true gift to astronomers because it contains a treasure trove of information about the Universe.

The graph below contains data points, extracted from the Planck data, and a curve. The curve goes straight through the data points, but it isn't simply drawn on. It is a theoretical prediction, beginning from a distribution of density differences at the Hot Big Bang as predicted by inflation, seeding sound waves through the particle soup of matter and dark matter that stop propagating when the CMB is released, and evolved using Einstein's Theory of General Relativity to a universe today consisting of 5 per cent matter, 27 per cent dark matter and 68 per cent dark energy. The numbers match the measurements of the constituents of the Universe we described earlier, built up from direct observations of the behaviour of stars and galaxies and the calculations of Big Bang nucleosynthesis.



The temperature fluctuations in the CMB as measured by the Planck Satellite. From Cox and Forshaw, *Universal: A Guide to the Cosmos*, Penguin Books, 2016.



Physicist and mathematician Richard Feynman speaking at Cal Tech University in Pasadena, California in 1959.

This is an absolute triumph – it's hard to overstate quite how remarkable the agreement is – and illustrates a very important point about modern science. One often hears so-called sceptics, or conspiracy theorists as they

are sometimes known, say that scientists are arrogant when they speak of near-certainties such as the Big Bang model. It's only a theory, they might say, or Galileo was persecuted for saying the Earth went around the Sun.⁷ The great Richard Feynman is often quoted; 'If you thought science was certain, well, that's just an error on your part.' If there is one truth in science, it is that there are no absolute truths as far as theories are concerned. There are facts; the Earth does go around the Sun and we are part of a galaxy of hundreds of billions of stars. Theories are different in that they are all models, and, as the saying goes, all models are wrong. The meaning of this is that we have no theories that we consider to be applicable in all circumstances. General Relativity does not work at very high-energy densities, and the Standard Model does not contain an explanation for dark matter, for instance. Having said that, we have confidence in theories that lead to predictions that can be checked, preferably by many independent measurements. Big Bang nucleosynthesis, coupled with our understanding of the CMB and astrophysical measurements such as the rotation rates of galaxies and the movement of galaxies in clusters, provide so many independent cross-checks. This reflects our understanding of physics across such a wide variety of fields from nuclear and particle physics to gravitation, that it is very hard to see how it can be argued that there was not a hot, dense phase in the evolution of the Universe many billions of years ago that forged the lightest chemical elements and produced the afterglow of the Big Bang in the form of the CMB. For a sceptical position to have any validity at all, the sceptic would have to advance a competing theory that did as well, or better, at explaining *all* these observed properties of the Universe simultaneously, and they would have to put a curve on the graph see [here](#) that goes through all the data points. This is very difficult, because removing dark matter, for example, and coming up with some other explanation for the motion of galaxies, will very likely break the description of the CMB, which uses the presence of dark matter particles in the primordial soup to explain the relative heights of the peaks on the graph. This is very often the case in science; the real power comes not from the explanation of one or two particular facets of nature, but from a single consistent explanation for a whole host of superficially unrelated observations.

Our cake is now very well-iced, but as we alluded to earlier, there is even more to Inflation than this because the theory is also able to explain why it

is that we observe precisely 5 baryons' worth of energy in the Universe today. The important and apparently mysterious thing is that five is a very special number.

R: At this point, I can sense your befuddlement, or maybe it's just my hope that my befuddlement is shared with the readers' befuddlement. But at times of physics befuddlement, Brian usually has a joke to ease the tension. This was first aired at Blackpool Pier when D:Ream's set was cut short by a power cut. My favourite physics joke is 'Heisenberg is speeding down the motorway. A policeman pulls him over. "Do you know how fast you were going?" asks the policeman. Heisenberg replies, "No, but I know exactly where I am."'

Now it's time for Brian's joke.

Why would astronomers be more excited about the number five than, say, 42, or 69? The reason for the excitement is that 5 baryons per cubic metre is a special value known as the critical density. The critical density is the density of matter and energy required to make the Universe 'flat'. If you've read the bit on General Relativity and the Friedmann Equation (see [here](#)), you'll already have met this concept. If you haven't read that bit, now's a good time! The important point is that this precise number is *extremely* special. Given no other information, it could have been anything at all, and astronomers were not unduly concerned before the late 1990s when it appeared to be around 1.5. They wouldn't even have minded if there were no dark matter and it was 0.25. Now that we measure the density of the Universe to be so close to the critical density, however, an explanation is demanded, not least because the Friedmann Equation tends to drive a universe that is not absolutely flat away from flatness over time. Our universe, in other words, must have been mind-bogglingly flat close to the Big Bang if it is still observed to be flat today.

An answer to this conundrum can be found, again, in the theory of Inflation. When we described the evolution of our universe from a time during inflation, through the Hot Big Bang and onwards to the release of the CMB, we considered a patch of space around a billionth of the size of a proton. The reason why we focused on this little patch is that it was destined to become our entire observable Universe 13.8 billion years later.

There would presumably have been other patches neighbouring ours during inflation, but we didn't follow those. Why not? If we had focused on a different patch, the same size as ours at the same time during inflation, then it too would have led to a roughly melon-sized region of space at the Hot Big Bang and a 100-billion-light-year-wide region of universe populated by trillions of galaxies 13.8 billion years later. The reason we're not so interested in this part of the Universe is that we can't see it because the galaxies it contains are so far away that light has been unable to reach us, and the light from the overwhelming majority of them will never reach us. The theory of Inflation therefore naturally describes a universe far larger than we can see today or will ever be able to see – a universe that may be infinite in extent, for all we know.

‘There could be so much space beyond our horizon, there are indeed other avatars of ourselves taking all possible decisions.’

– Martin Rees, The Right Honourable The Lord Rees of Ludlow, Series 6, Episode 5 (16 July 2012)

‘In the time of Shakespeare, thunder and lightning and rain were the matter of witches. Today it's part of science. We don't know if the Universe is infinite or not.

Today that is metaphysics but some day it will become part of science.'

– Professor Carlos Frenk, Series 10, Episode 5 (4 August 2014)

The vast scale of the Cosmos beyond the horizon suggested by inflation has an immediate consequence in that it explains why our observable Universe appears flat; the great puzzle that the Universe today appears to be precisely at the critical density of 5 baryons' worth of energy per cubic metre.

We can explain the reason with a simple analogy. Think about a 1-km-square region of the surface of the Pacific Ocean on Earth. On a calm day, it would appear perfectly flat. If we extend our region of interest to the entire Pacific Ocean, however, we'd see that the surface is curved because the Earth is a sphere. There is no great mystery about the flatness of a small piece of ocean; we must look on distance scales of the order of the radius of the planet to see that it is curved. In the same way, if the Universe is significantly larger than the observable Universe, we will always measure the observable Universe to be flat. The entire Universe may or may not be flat; we have no way of knowing, but our patch will be. Inflation therefore provides a natural explanation for the seeming coincidence that if we add up all the matter, dark matter, radiation and dark energy in the Universe today, we get the magic 5 baryons'-worth of energy per cubic metre corresponding to a flat universe.

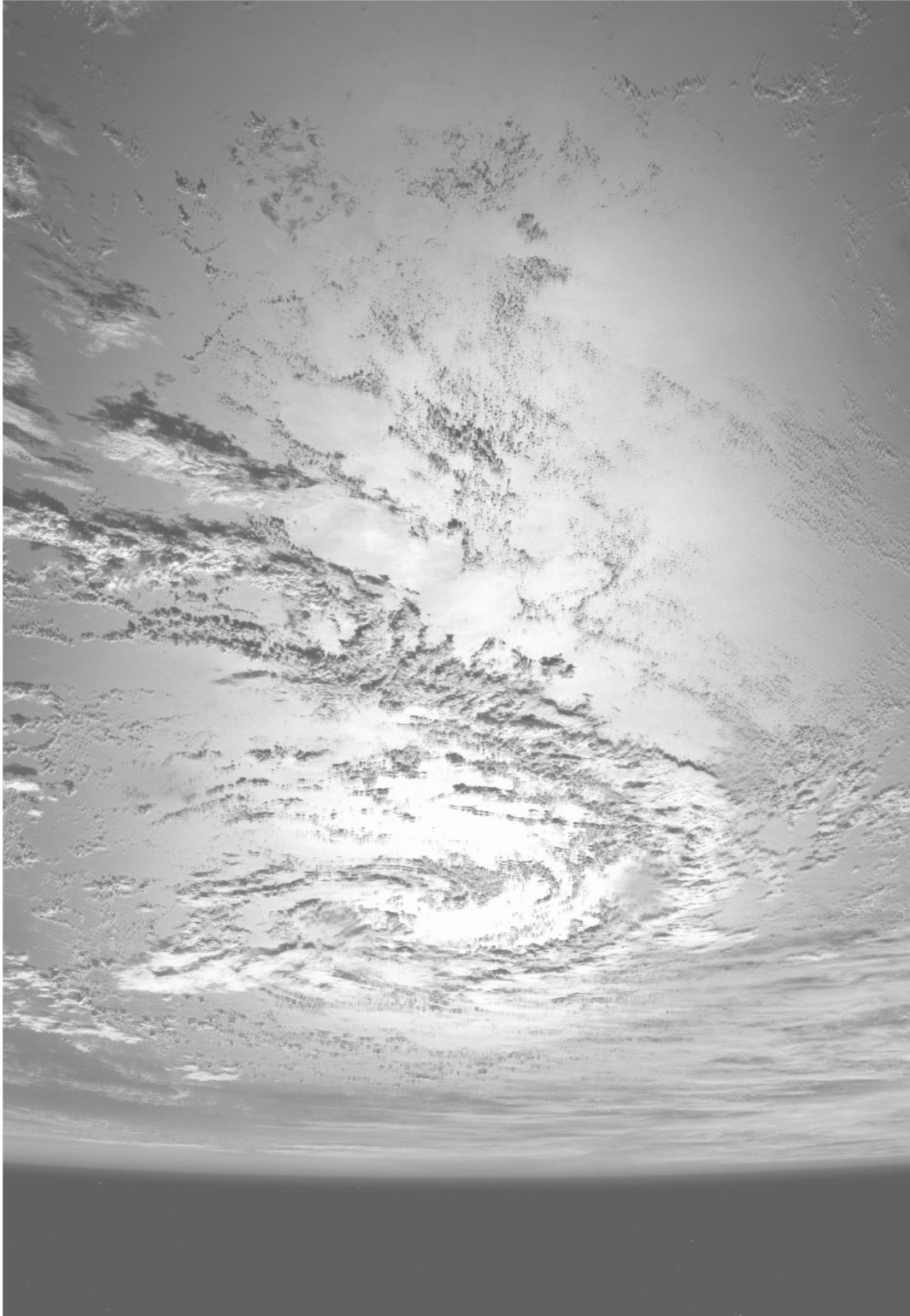
This is state of the art regarding our knowledge of the history of our universe and its constituents, and none of this is speculative or controversial. Even inflation, the most debated and least understood piece of what we've described, is considered part of what is sometimes called The Standard Cosmology – which is to say that it is the dominant paradigm at the present time. The model fits the data, and any new theory will have to do a better job than this.

We can now state the recipe for our universe. Inflation delivers a universe very much larger than the part we can see. It also delivers an almost but not quite uniform distribution of particles after the Hot Big Bang. 13.8 billion years later, the matter and energy content of the Universe had evolved into the very specific proportions of 5 per cent matter, 27 per cent dark matter

and 68 per cent dark energy, the initial density fluctuations had collapsed to form stars, planets and galaxies, and nuclear physics and chemistry had conspired to produce a living civilisation capable of working all this out. The atoms of the Universe had managed to invent a creation story that is likely to be correct.

This is surely mind-blowing enough, and a great testament to human ingenuity and creativity, but it's not the end of the scientific creation story. There is an additional possibility suggested by inflation that some cosmologists would go as far as to describe as a further prediction. This is probably a little too strong, given our current understanding, but if correct, the theory really does begin to approach the fundamental questions, concerns and philosophical challenges inherent in all stories of creation.

R: Will this speculation include String Theory? I started reading books about our possible universe of tiny vibrating strings, but then some theoretical physicists told me they had no time for that theory at all until the tiny vibrating strings were a little more concrete. For this reason, I have thought it best not to spend too much time reading about String Theory in case I spend a decade or so immersing myself in trying to understand it and just as I am able to say, 'Oh, I get it now', there is an announcement from inside the volcano of the International Council of All Physics saying, 'String Theory has now been declared null and void, we will be continuing with the new theory of very, very small spinning plates on the back of an elephant living inside a very big Magpie.'

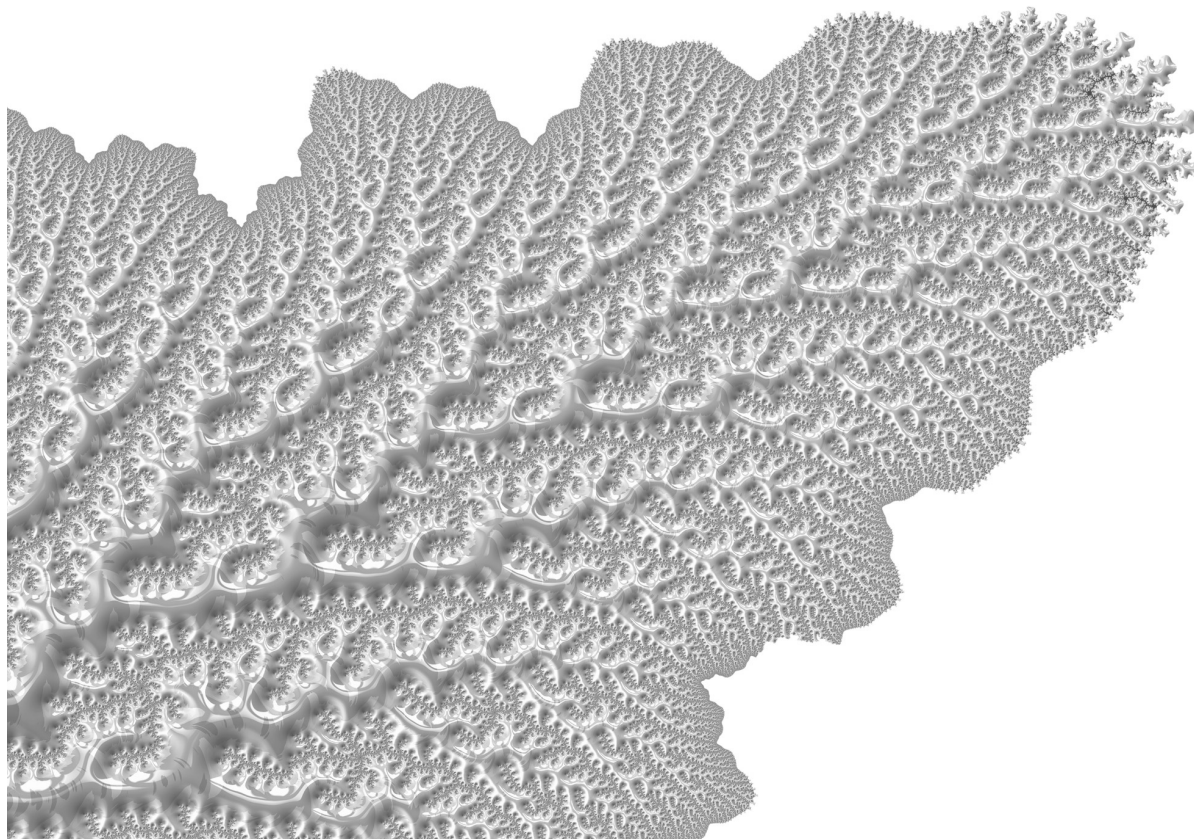


German ESA astronaut Alexander Gerst took this image of Earth reflecting light from the Sun whilst aboard the International Space Station (ISS) in 2014.

We have said that Inflation naturally runs out of steam, leading to the Hot Big Bang. This was certainly true in our region of space (if the theory of Inflation is correct), but must it be true everywhere? Recall the fluctuations in the energy of the inflaton field – the stormy sea – which seeded the density fluctuations in our universe. What if the height of the waves in the inflation ocean were so great in some regions that inflation didn't slow down but sped up? As the stretching of the rest of the surrounding space slowed, these regions would quickly come to dominate the Universe, and inflation would continue. Such a picture suggests that places like ours, where inflation has stopped, may be the exception rather than the rule. This theory is known as Eternal Inflation, because inflation never stops everywhere. The patches where it does stop spawn bubble universes, of which ours is one, and of which the observable Universe is a tiny part. This picture of a neverending branching fractal tree of bubble universes, riding on the back of inflating space, is known as the inflationary multiverse. It is quite natural, and many cosmologists find it compelling and appealing because it may offer the solution to one of the greatest of mysteries.

As we have seen, General Relativity and the Standard Model, perhaps suitably extended to explain dark matter and dark energy, provide a recipe to build our universe, but they certainly do not deliver a unique recipe. There are over 30 numbers which must be inserted 'by hand' from experimental observations to produce the Universe that we see today. These numbers describe the masses of the fundamental particles, the strengths of the forces, the amount of dark energy in the Universe today, and so on. If these numbers are changed by even small amounts, the resulting universe can be very different. In a universe with weaker gravity, if all else is kept the same, stars and galaxies do not form. Changing the relative strengths of the electromagnetic, weak and strong forces can result in very different nuclear physics, which can lead to a universe devoid of large quantities of carbon and oxygen, and therefore unlikely to support life. Too much dark energy and the Universe expands too quickly for stars to form. It is almost as if the laws of nature were fine-tuned from the beginning with our existence in mind. We don't know whether we are allowed to tweak all these numbers individually, because we do not have a theory that unifies the Standard Model and General Relativity into some form of quantum theory of gravity; the strength of gravity may be related to the strengths of the other forces in some way, for example. That being said, this apparent fine-

tuning of the laws of nature is not a trivial observation, and leads some towards design arguments which posit the existence of a designer or creator. It's possible that we are just lucky, and of course we must observe a universe that permits us to exist, but eternal inflation may provide a different explanation when coupled with String Theory.



This fractal image embodies the complexity and beauty of the shapes seen in Nature.

String Theory is our most mature, although undoubtedly incomplete, attempt to build a quantum theory of gravity. It posits that the fundamental building blocks of the Universe are tiny vibrating strings of typical size around 10^{-35} m. This is a hundred billion billion times smaller than a proton. String Theory has had some notable successes; General Relativity and the Standard Model seem to emerge as low-energy approximations to this deeper underlying theory. There are two apparent problems, however.

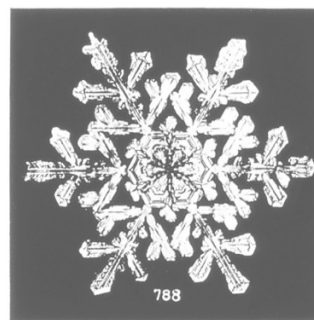
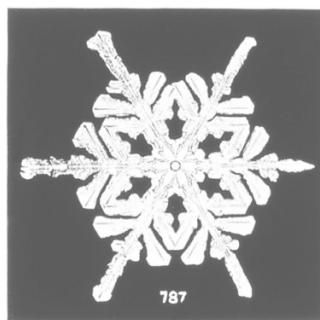
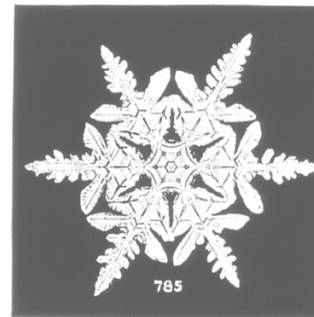
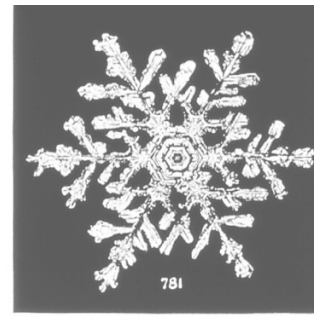
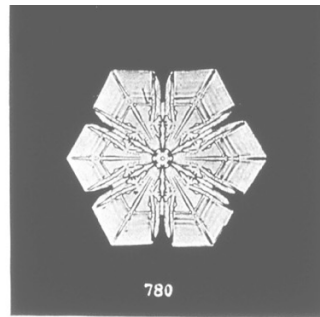
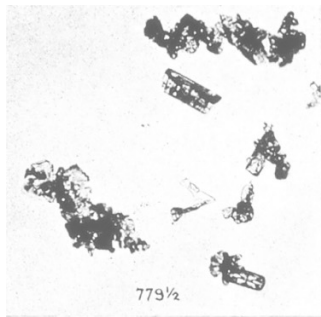
One is that the mathematics of String Theory only works in ten dimensions, whilst we appear to live in a universe of only four; three dimensions of space and one dimension of time. These extra dimensions can be curled up into tiny shapes, however, such that we wouldn't perceive them directly. The picture is that at every point in our three-dimensional world there is a complex tangle of extra dimensions that are too tiny to see, even with giant microscopes such as the Large Hadron Collider. In String Theory, the way these dimensions are curled up leads to the laws of nature that we observe; the strength of gravity, the number of particles and their interactions, and so on. This is very encouraging, and for a time many physicists thought that they could derive a single shape for these extra curled-up dimensions which would amount to a complete theory of our universe. Our universe would be the only possible universe, and we would, as Stephen Hawking memorably wrote at the end of *A Brief History of Time*, know the mind of God.

In the early decades of the twenty-first century, however, String Theorists' hopes appeared to have been dashed because they discovered that the extra dimensions can be curled up in many ways. 'Many' is an understatement, because there are around 10^{500} different possibilities, a number that far exceeds the number of atoms in the observable Universe.

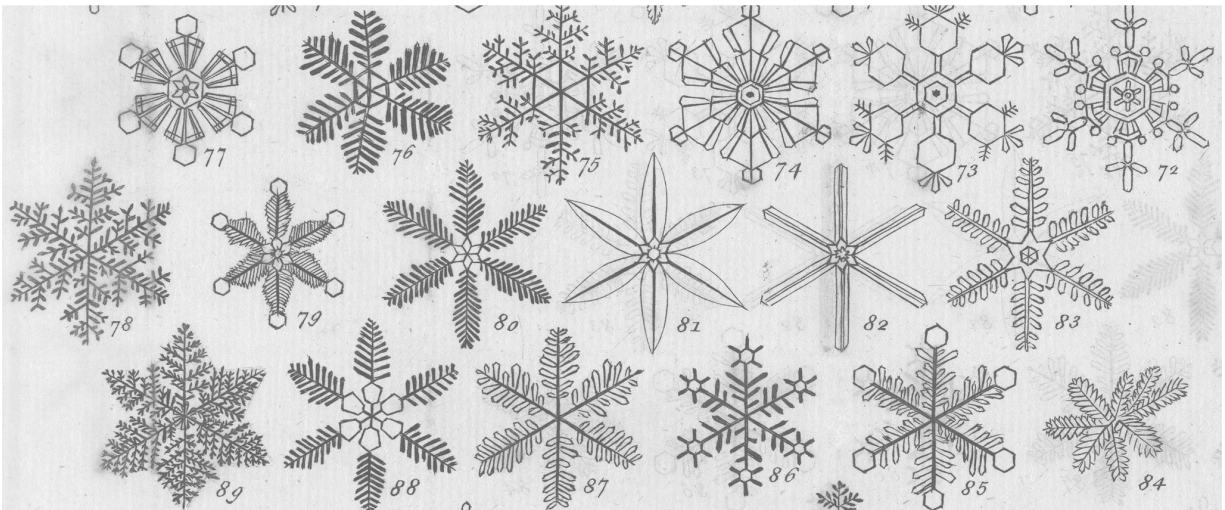
This appears to be disappointing, to say the least, but when merged with the theory of eternal inflation this daunting explosion of possibilities becomes a feature.

If we run time backwards from the Hot Big Bang and into the inflationary epoch, the energy density in the inflaton field must increase. This is because, as we approached the Hot Big Bang, the energy in the inflaton field certainly decreased otherwise inflation wouldn't have stopped, at least in our region of space. As we go back in time, we very quickly reach energies so high that space and time melt away and lose their structure. This means that the shapes of the curled-up dimensions melt away, too.

We can therefore imagine the structure of space and time, complete with the curled-up extra dimensions, crystallising out during inflation as the energy density falls below some critical value. The formation of bubble universes is then analogous to the formation of snowflakes; each one different but created from the same underlying physical laws and made of the same basic stuff. Each snowflake is a universe with different emergent laws of nature.



These captivating images, taken by Wilson 'Snowflake' Bentley through a light microscope attached to his camera, were the first snapshots of snowflakes captured on camera in January 1885.



In this snowstorm of universes created by eternal inflation, every possible configuration of dimensions will be made real, possibly an infinite number of times. This is the explanation for why our universe appears so perfectly fine-tuned for life. It is inevitable that a universe like ours should exist, because all of the 10^{500} possibilities exist in the multiverse.

This still leaves the question of the existence of the inflationary multiverse. Why is there anything and not nothing? Why does String Theory exist? Where did the inflaton field come from? Could it be that a full understanding of String Theory would demand that something like eternal inflation *must* exist? Or will we be forever condemned to face the intractable problem of existence? This is not currently the province of science, and we must stop.

There is a beautiful book written by Johannes Kepler⁸ called *The Six-Cornered Snowflake*. He wrote it after a snowflake landed on his coat as he walked over a bridge in Prague in December 1610. He muses on the structure of snowflakes, pomegranate seeds, hexagonal bee-hives and all sorts of patterns in nature. He didn't reach a conclusion. How could he, in a world before we knew of atoms and molecules, or Newton's theory of gravity? It was a great leap that Kepler's own study of planetary motion did much to enable. Civilisation in 1610 didn't have the accumulated knowledge for anyone to have any chance of understanding the structure of a snowflake. But understand it we have.

Kepler finishes the book with humility and the melancholic hint of a curious man who knows his thoughts are carrying him far ahead of his time:

‘... seeing how much remains to be said on this subject before we know the cause, I would rather hear what you think, my most ingenious man, than wear myself out with further discussion. Nothing Follows. The End.’

– Johannes Kepler



The Standard Model of particle physics

The Standard Model of particle physics describes all the known fundamental particles of matter and their interactions, excluding gravity. There are twelve particles of matter arranged into three families, as shown below, opposite. The protons and neutrons that make up atomic nuclei do not appear in the figure because they are not fundamental particles; they are made up of smaller constituents known as quarks. Two up quarks and a down quark make up a proton, and two down quarks and an up quark make a neutron. The quarks are held in place by the strong nuclear force, which is carried by a particle called a gluon. In quantum field theories like the Standard Model, forces are transmitted by the exchange of particles.

Atoms are made up of protons, neutrons and electrons. The electron is a fundamental particle and appears in the first column of the figure beneath the up and down quarks. The electron is held in place around the nucleus by the electromagnetic force carried by the photon, familiar to us in everyday life because photons are particles of light. The first family of particles is completed by a particle called the electron neutrino. Neutrinos are not found inside atoms, but they are an essential part of our world because they participate in certain types of nuclear reactions, for example, those that are taking place now in the core of our sun. The Sun shines by converting hydrogen nuclei, single protons, into helium – two protons and two neutrons. The third fundamental force, known as the weak nuclear force, can convert protons into neutrons, or more specifically up quarks into down quarks, and vice-versa. When this happens, a neutrino is created. The weak force is carried by the W and Z bosons. It is this part of the Standard Model that is used to calculate the proton to neutron ratio created in the first three seconds after the Hot Big Bang. After the first three seconds, temperatures and densities have already fallen below those at which these weak interactions are likely to transform protons into neutrons.

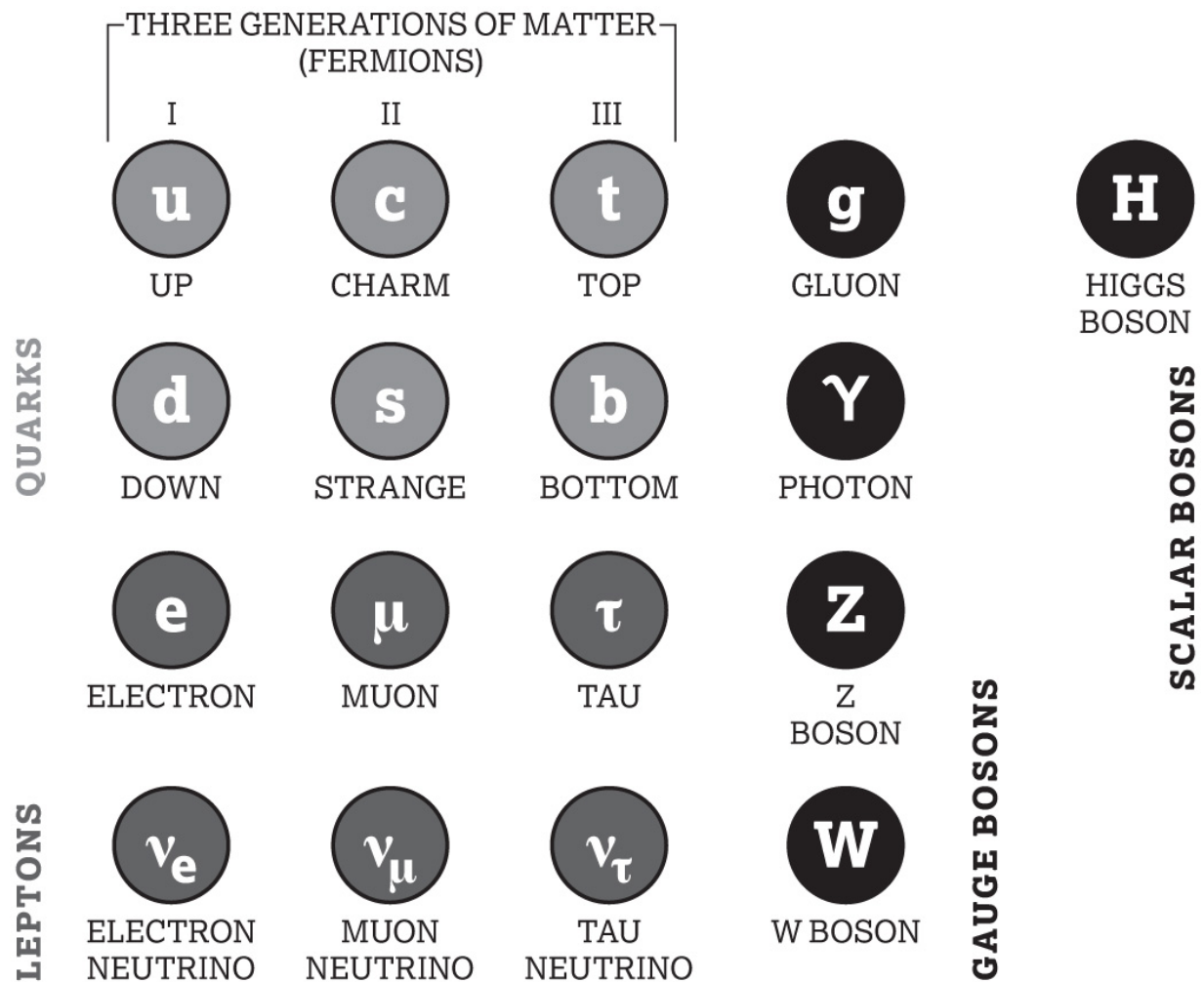
There are two further families of particles, which are identical to the first family in every way apart from their mass. The charm quark, for example, has identical electric, strong and weak charges as the up quark, but is significantly more massive. Likewise, the muon is identical to the electron, save for its increased mass. The reason for this pattern is unknown. As an aside, another triumph of Big Bang nucleosynthesis is to provide one of the most powerful constraints on the existence of further families of particles. The expansion rate during Big Bang nucleosynthesis is controlled primarily

by the density of photons and neutrinos in the Universe. If there were another light neutrino beyond the three in the Standard Model, the expansion rate would have been different. This leads to a different amount of time available for Big Bang nucleosynthesis, and therefore different predictions for the relative abundancies of hydrogen, helium and deuterium.

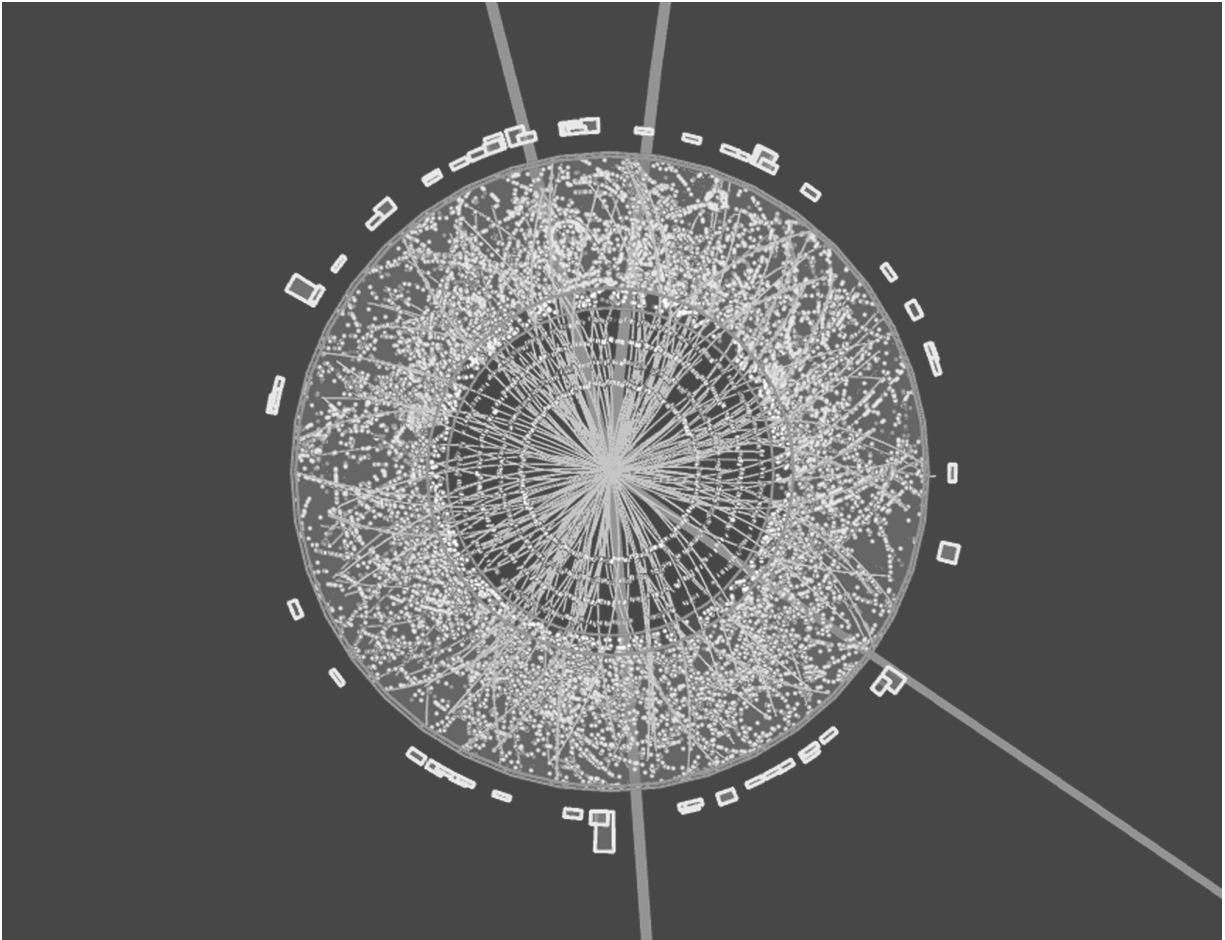
The final piece of the jigsaw is the Higgs boson, discovered at the Large Hadron Collider at CERN in Geneva in 2012. In the Standard Model, particles acquire their masses through interactions with the Higgs boson; the stronger the interaction, the more massive the particle. It is suspected by many physicists that the masses of the neutrinos, which are tiny in comparison to the other matter particles, may be different in origin, but this is considered as physics beyond the Standard Model.

The Standard Model is highly predictive – the Higgs particle was one of its predictions – but it is certainly not the final word. It does not contain dark matter particles, for example. Neither does it explain why the forces are the strength they are, or why the matter particles interact with the Higgs boson in the way that they do. In total, there are around 30 numbers describing the behaviour of the particles that must be measured in experiments and inserted by hand.

We do not know if the particles in the Standard Model should be considered fundamental, which is to say that they really are structureless and not made up of smaller constituents. All we can say with certainty is that our current microscopes, of which the Large Hadron Collider is the most powerful, reveal them to be structureless and of no discernible size.



The 12 particles of matter, four Gauge bosons and the Higgs boson that make up the Standard Model of particle physics. All the matter particles have corresponding anti-particles, which are not shown.



This graphic shows one of many particle collision events that have been recorded by scientists at CERN in their quest to discover the Higgs Boson.

General Relativity and the Friedmann Equation

Einstein's Theory of General Relativity was published in 1915 and is the basis for all modern-day cosmology. The theory can be applied to the entire Universe, and under the simplifying assumption that on the very largest scales matter and energy are distributed uniformly, Einstein's equations reduce to the most useful equation in all of cosmology, the Friedmann Equation:

$$H^2 = \frac{8\pi G}{3} \rho - K \frac{C^2}{a^2 R^2}$$

H is the Hubble Constant, which tells us how fast space is expanding at any given moment in time. The name is not great, because it isn't a constant, and for this reason it's sometimes referred to as the Hubble

parameter. The Hubble constant today is around 70 km/s/Mpc, where 1 megaparsec is approximately 3.3 million light years. This says that if two galaxies are 3.3 million light years away, they will be moving apart due to the expansion of space at a speed of 70 km/s. If they are 10 million light years apart, they will be moving apart at 210 km/s and so on.⁹ G is Newton's Gravitational Constant, which tells us the strength of gravity, and c is the speed of light. These are two of the 30 or so fundamental numbers that characterise our universe. In Einstein's equations, G tells us how much spacetime warps, curves or stretches in response to a given amount of mass or energy. ρ is the average density of the Universe, made up of matter and dark matter, radiation and dark energy. The density of each of these components changes in a different way as the Universe expands. Dark energy, for instance, stays constant as the Universe expands, whereas the matter density becomes diluted. The Friedmann Equation says in mathematical terms what we have said in words: The expansion rate of the Universe changes in a way determined by the matter and energy within it.

The final term on the right-hand side of the equation describes the geometry of space, which also governs the expansion rate. In particular, $K = +1$ for a spherical geometry, $K = -1$ for a hyperbolic geometry and $K = 0$ for a flat geometry. The reason that there are only three possible geometries in the Friedmann Equation is our initial assumption that matter and energy are uniformly distributed throughout space; the Universe is the same in every direction. Since matter and energy are doing the curving, it follows that space must be curved in the same way in every direction. In this case, there are only three possibilities; space can be curved like a sphere ($K=1$), a saddle ($K=-1$) or be perfectly flat ($K=0$). Perhaps you can see how we came up with the value for the critical density in the main text, which is the special value of ρ in a flat universe (at a given time, fixed by the value of the Hubble Constant): Set $K=0$, and

$$\rho = \frac{3H^2}{8\pi G}$$

The term a is known as the scale factor, and is defined as being equal to 1 today. In our expanding universe, a was smaller in the past and will be larger in the future. The Hubble Constant can be written in terms of the scale factor:

$$H = \frac{\dot{a}}{a},$$

where \dot{a} is the rate of change of the scale factor. This makes it clear that the Hubble Constant isn't a constant, but changes with time.

The term R is, roughly speaking, the radius of the Universe. You can see that if we make the Universe very much bigger than the piece we can see, R is very large and the second term on the right-hand side of the equation is very close to zero, leaving us with a universe at the critical density, whether or not $K = 0$. This is the case in models of inflation, as discussed in the text.

Given the Friedmann Equation, perhaps you can see how measurements of the Hubble Constant for distant supernova explosions told astronomers that there was something missing in ρ , the inventory of the Universe, and led to the discovery of dark energy.



How to Bake a Universe (Please allow time)



INGREDIENTS

Nothing

METHOD

To start your universe, you will need to purchase nothing, but it is important to choose nothing with a lot of potential. Many of the nothings sold at lower-end supermarkets are low in price because they have no potential, or short-lived potential. It is worth shopping around and spending a little bit more.

Leave your nothing to stand.

Set your oven's timer to Planck Time.

You will notice the oven's timer ping in about 10 to -37th second, when the nothing creates time and space.

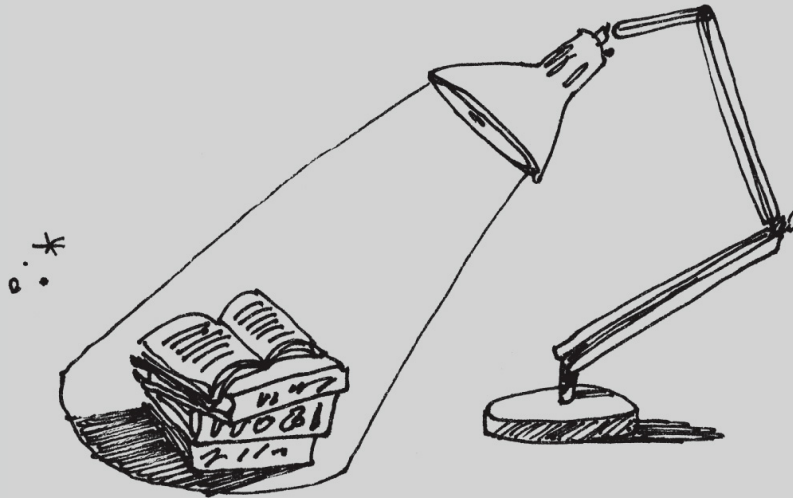
It is important to make sure your oven is roomy as your universe should rise very rapidly.

If your universe does not rise and spread rapidly, check you have sprinkled in some Higgs Field.

Take your universe out of the oven and allow to cool.

You may notice smears of dark matter and dark energy, do not try to wipe them off, they will prove very useful. Do not worry if you cannot see the dark energy and dark matter, you can go poking around in the mix looking for it but it might disturb the expansion.





If all is going well, you should notice the development of four forces – strong nuclear force, weak nuclear force, electromagnetic force and gravity. If you can't see them, return your nothing to the shop and complain that nothing did not contain all the ingredients it said on the label.



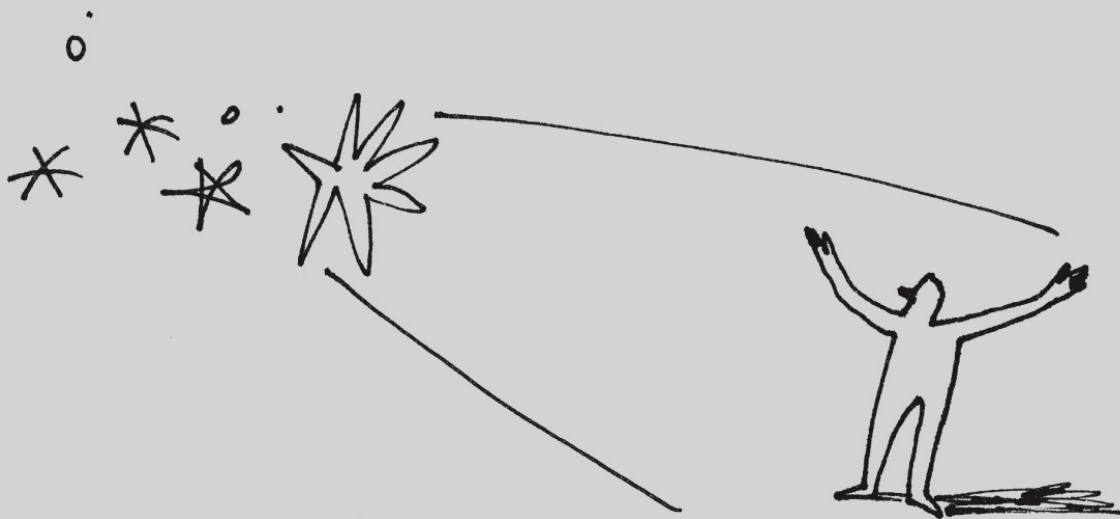
After ten seconds you should see electrons and positrons, do not worry about them annihilating each other, you may get a slightly burnt caramel smell.

The next stage requires patience. Have some good books to fill your time, in fact, have all the good books to fill your time. This will be a good time to read *Ulysses*, *Remembrance of Things Past* and Alan Moore's *Jerusalem*.

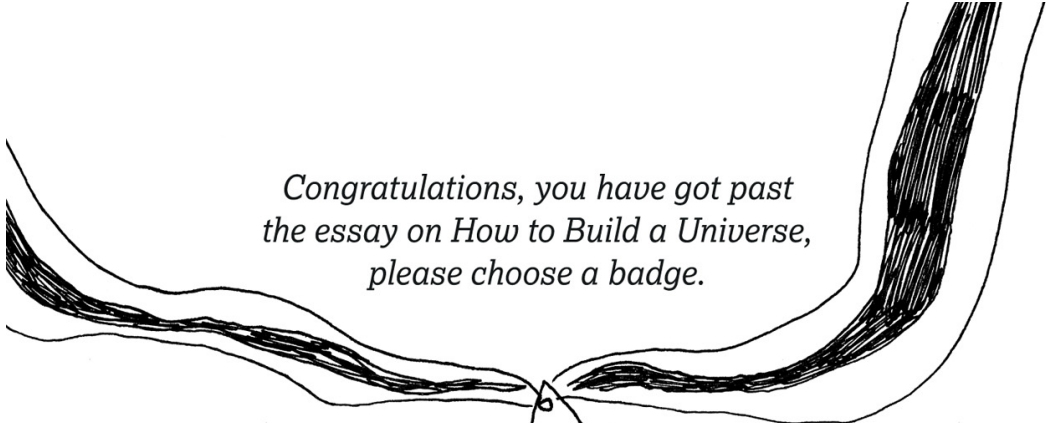


After 200 million years, you should be able to turn off your reading light and use the first starlight instead. Now prepare for quasars and galaxies.

Congratulations, you have made your first universe, now prepare to rule it like a malevolent deity or with utter indifference.



DISCLAIMER: *Monkey Cage* takes no responsibility for any household damage or existential crises should your universe lead to sentient life perpetually complaining of the confusion of existence.



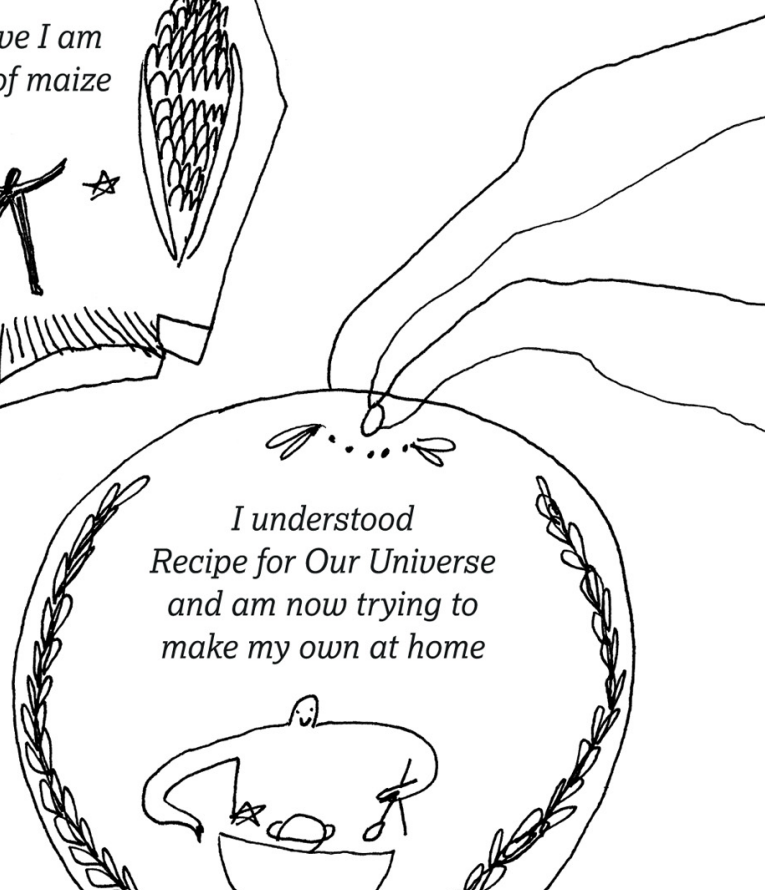
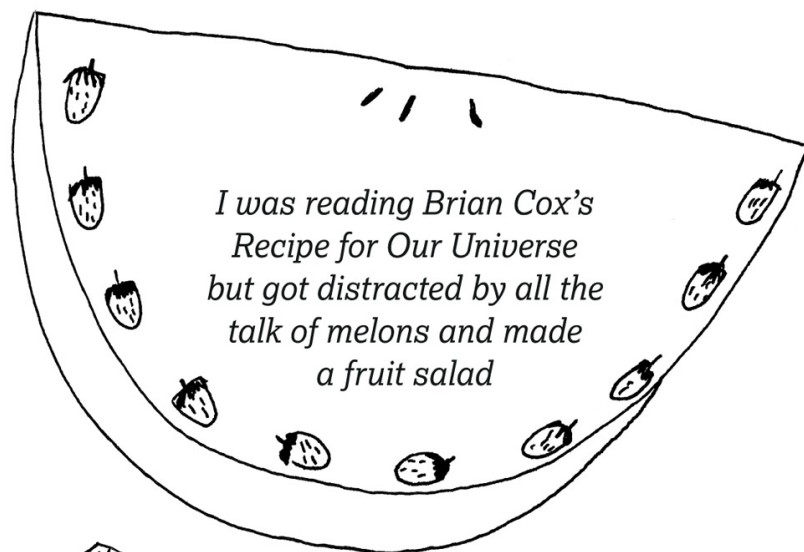
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the essay on How to Build a Universe,
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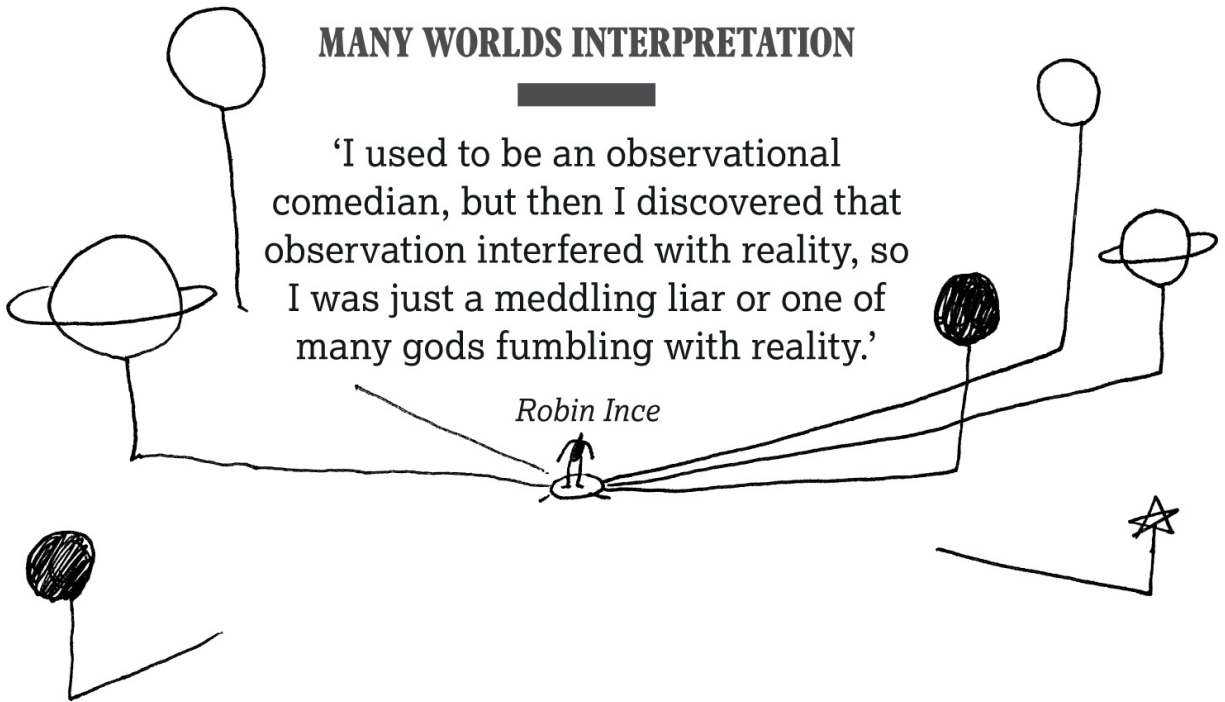


*I understood Brian Cox's
Recipe for Our Universe*



*I read Brian Cox's
Recipe for Our Universe*





We used to be the centre of the Universe.¹ The Sun went around us.² There were a few other planets and there were a few stars for a decorative backdrop.³ Then it turned out that the Sun was the centre of it all⁴ and our solar system was part of something much bigger, with billions of stars in the galaxy. Then it turned out that our galaxy was one of billions.⁵ Meanwhile, we were usurped from being an animal separate from all the grubby, snuffling and nude animals. We were as related to yeast as the stoats and guppies and all the burping and procreating things grown from the same common ancestor. But at least we were in charge of our minds and our actions, until research suggested that we merely believe we have made conscious decisions, and that in fact our mind merely creates a back story so that the you of you thinks it's in charge. If neuroscience is not enough to unseat you from your arrogance, then quantum physics comes along with a possible interpretation that states that at every point of decision-making there is a paring off of worlds so that you make every version of the decision – and there goes free will. You have made every decision, it's just that in this world, you made the decision that went a particular way, when in fact at your point of judgement you have split into many, and that happens again and again and again.⁶

You made the decision to stop and browse through this book.
You made the decision not to and are instead about to browse through a book by David Icke.
You didn't even come into the bookshop in the first place as you made a decision some years ago to become an international unicycling assassin.²

Don't spend so long agonising over your menu choices, you will have eaten everything even if you and you and that other you that has no idea why it chose haggis and gingerbread salad with peacock eggs will have tasted it all somewhere in an unreachable quantum suggestion.

Pragmatically, we are not certain just how philosophically useful the idea of many worlds is to the way you live your life, unless you will be living it by constantly referring to the quantum computer handily housed in the wristwatch of your dreaming.

Is there a solace in thinking, 'well, I certainly married the wrong person on this occasion, but hopefully in most of the quantum multiverse I married someone else or went to live in isolation in a cave with a proximity to an audible whale song'?

'I like it because it means that somewhere I finished my PhD.'

Ben Miller, Series 10, Episode 5 (4 August 2014)



Following a show in which we briefly discussed the possibility of free will and parallel worlds, a listener sent a letter. They had a romantic quandary. They wanted to ask someone out on a date but could see no point if free will was an illusion. We replied that even if we told him that free will was

most definitely an illusion he would still appear to make a decision by not doing anything about it. We added that if the Many Worlds Interpretation of quantum theory is correct, in at least some of the worlds he would ask the person out, then in some of the worlds it would go swimmingly and lead to marriage and delight, and in others there may be some murders. This did not help.

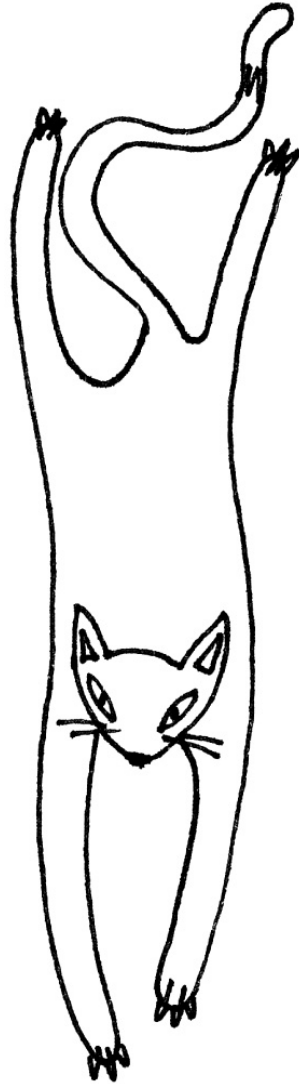
We received a reply some weeks later:

‘Thank you very much [this was written in a sarcastic font]. I asked her out and she said no in front of my friends and I looked like a right idiot. I hate science.’

Since then, we have ceased to operate the Agony Uncles wing of *The Infinite Monkey Cage*.

‘If there are an infinite number of parallel universes, where all possibilities exist, there logically must be a parallel universe without any parallel universes in it, and I’m wondering if that might be the one we are in?’

John Lloyd, Series 6, Episode 5 (16 July 2012)



Many Worlds Interpretation is not the same as the multiverse, although it appears to have many of the ramifications of a universe of infinite size. If the Universe is of infinite size, everything that is going on now, right now, is happening elsewhere. This is different to the inflationary multiverse, which proposes that this universe is not the only one and there are other 'bubble universes' with different physical laws.⁸ Many Worlds springs forth from quantum behaviour. (It is around this time, reader, that you realise this bit is being written by Robin and not Brian, but in another world, Brian wrote this bit and it made a lot of sense.⁹) There is a superposition of each new possibility and each potential decision. As I make the decision I have collapsed the wave function¹⁰ and the dead cat/live cat reality is upon us, but there is not a single dead cat. Many Worlds states that feline wellness

will exist in all its varieties, just in different worlds. While one world is home to a tear-faced cat burial, another is filled with delight at the vibrancy and joie de vivre of the cat, even though the family are still a bit at a loss as to why Dad put the cat in there in the first place.^{[11](#)}

‘There would exist other universes where there weren’t people alive to host popular programmes about science. Heaven forbid, Brian.’

Ben Miller, Series 10, Episode 5 (4 August 2014)



Writing about Schrödinger’s cat in popular culture for a British newspaper, I made the mistake of reading the bottom half of the internet the day after the piece went up. People were furious that ‘foreign scientists’, ‘probably financed by the European Union’, were being paid to torture cats in the name of particle physics.^{[12](#)} I made the mistake of butting in to explain that

The comments in the other world I peeked into were a lot more positive.

John Lloyd, Series 6, Episode 5 (16 July 2012)

1 This is a charitable way of putting it.

³ Another favourite question at this event in Edinburgh was an old man who asked ‘Is it true that if I wore a lead lifebelt I would be able to pass through a black hole unscathed?’ Sadly, the answer was no. He looked very disappointed, I think he’d been working on that lifebelt for quite some time.

[illegible]

2 It wasn't that simple. Galileo didn't really provoke the ire of the Church until he chose to move beyond the simple reporting of his scientific results and decided to champion a particular theological interpretation, which brought him into direct conflict with the accepted interpretation of the Bible at the time. This has led many historians to conclude that Galileo may not have been placed under house arrest in 1633 if he'd 'stuck to science' and stayed out of theology.

8 Johannes Kepler also wrote *Somnium*, which some credit as the first work of science fiction. It includes an imagined view of the Earth from the Moon, and an appearance from Tycho Brahe, whose high-precision astronomical observations were central to Kepler's development of his laws of planetary motion. Brahe was a renowned astronomer who had a nose made from gold, having lost his

original nose in a duel over mathematical equations. The nose he was buried with turned out to be brass, which is probably no great mystery. Brahe had a pet elk that died when it got drunk and fell downstairs.

⁹ We are ignoring the possibility that the galaxies are interacting with each other gravitationally or heading towards or away from each other with some pre-induced relative speed. This is known as the proper motion. For galaxies that are separated by hundreds of millions of light years, the proper motion can be neglected, and the speed at which they move apart is entirely determined by the expansion of space. As an example, the Andromeda Galaxy, our nearest neighbouring large galaxy, is currently 2.5 million light years away but is heading towards us at around 110 km/s. This proper motion wins out over the expansion of space between two objects that are so close together in cosmic terms. As a result, the two galaxies will collide and merge in approximately 4 billion years' time.

¹ Brian: No we didn't, we used to imagine that we were the centre of the Universe.

² Brian: No it didn't, see [footnote 1](#).

³ Brian: You could just about get away with this if by 'a few' you mean 10^{24} .

⁴ Brian: No. The Sun isn't the centre of it all (see [footnote 1](#)), it's not even the centre of the Solar System, although the centre of mass of the Solar System is inside the Sun.

⁵ Brian: Bravo!

⁶ Brian: What's the collective noun for a quantum superposition of Robins?

⁷ Brian: With this, I've decided to stop annotating Robin's meditation. There is really no more to say. I'll only interject further if I see something factually inaccurate.

⁸ Brian: For a discussion of the Inflationary Multiverse, see [here](#) ('The Recipe for Our Universe').

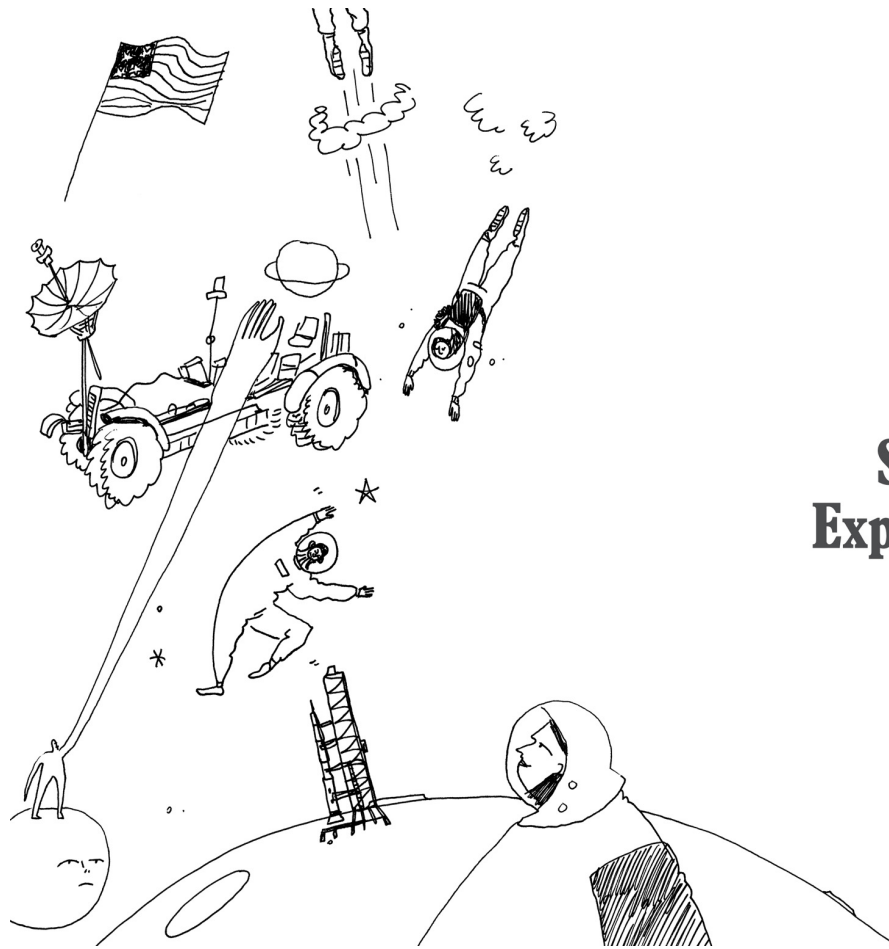
⁹ Brian: They already know it's written by ROBIN if they are looking at the footnotes, but nobody looks at footnotes.

¹⁰ Brian: The wave function does not collapse in the Many Worlds Interpretation of quantum mechanics. See [footnote 9](#).

¹¹ Brian: For a discussion of the Many Worlds Interpretation of quantum mechanics with less artistic licence, see Chapter 2 ('[Life, Death & Strawberries](#)').

¹² Brian: I don't understand why people would be upset if 'foreign scientists' were financed by the European Union. The other option, presumably, is for them to be not financed by the European Union, and therefore by the UK alone. I'm sure the sort of person you are referring to would find this even more objectionable.

¹³ Brian: Objection. Ah, sod it. I'm going to stop adding footnotes and read some Philip K. Dick.



No.4

Space Exploration

A DIFFERENT PERSPECTIVE

Why go into space?

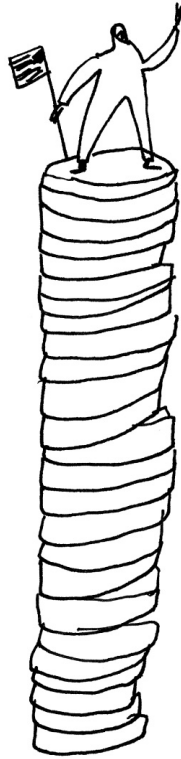


Human spaceflight is a magnificent and divisive endeavour. It's magnificent because it represents exploration at the physical frontier of our world, with all the challenges and romance that this entails. It's divisive because it's expensive. My personal view is that human spaceflight is critically important to our future. That's a borderline content-less statement without

qualification; of course it will be important for us to live and work beyond Earth in the far future. We will have to deflect an asteroid to survive, access new raw materials and expand to Mars and beyond, sometime. The more challenging argument that I want to make is that the future is the next few decades.

The first thing to note about human spaceflight is that we have been doing it for over half a century, and we know a lot about it. The biggest single commitment was the Apollo Program, or Project Apollo. This was conceived as an evolution of the single-seat Project Mercury, which saw Alan Shepard become the first American in space in May 1961, and was given focus, funding and ambition by John F. Kennedy in a request to Congress that same month:

‘I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to the Earth. No single space project in this period will be more impressive to mankind, or more important in the long-range exploration of space; and none will be so difficult or expensive to accomplish.’



It's notable that Kennedy used the word expensive, which is rather unusual for a politician when making a budget request, but there is a difference between spending and investment that human spaceflight brings into sharp focus, and which too few politicians appreciate. In 1989, President George H. W. Bush noted that Apollo provided 'the best return on investment since Leonardo da Vinci bought himself a sketchpad'.¹ The NASA budget in the 1960s was large by R&D standards, but not particularly vast relative to total government expenditure. The cost of Apollo was T200 billion at today's prices, with a peak spend in 1966 of 4.41 per cent of the federal budget, equivalent to T40 billion today. To put that in context, it is less than the UK's current yearly debt interest payments. A series of academic studies have assessed the investment return; one of the most widely quoted carried out by Chase Econometrics in 1976 found that the historic rate of return from NASA R&D spending was 43 per cent.² Multiple studies have shown similar investment returns of between T7 and T14 for every dollar spent over the period of a decade. In broad terms, it's not too difficult to understand where the returns came from. The Apollo Program represented a large economic stimulus directed into high-value, highly skilled jobs in science and engineering, spread very cleverly across the United States.

Apollo supported 400,000 highly skilled jobs in over 20,000 companies, and the average age of the engineers in Mission Control when Armstrong and Aldrin walked on the Moon was 26. These engineers didn't just vanish when Apollo came to an end. They went out into the wider economy, working for Boeing, General Electric, Lockheed Martin and other aerospace and technology companies large and small, laying the foundations of American economic and technological dominance in the last quarter of the twentieth century.



Human spaceflight isn't expensive when considered in these terms. It would have been more expensive not to go to the Moon, in the sense that US GDP would almost certainly have been lower in 1980 without Apollo, unless somebody could have come up with a better investment strategy. The economic return, however, is not the primary reason I consider human spaceflight to be so important.

Kennedy's best-remembered Moon speech was delivered at Rice University on 12 September 1962. Why go to the Moon? Here is Kennedy, in soaring prose devoid of the cynicism and almost naïve in optimism – naïve, save for the fact that this mission was completed.

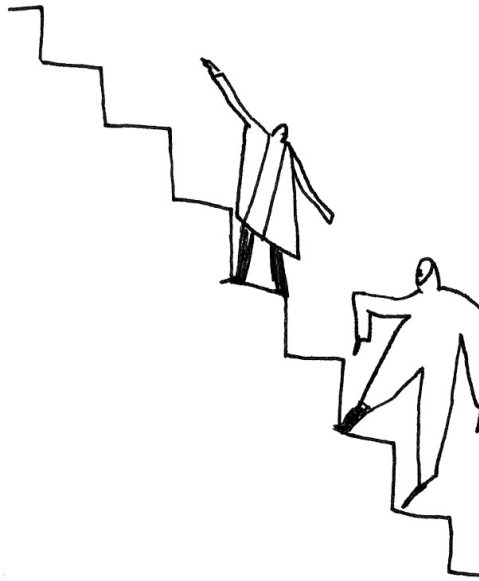
'We set sail on this new sea because there is new knowledge to be gained, and new rights to be won, and they must be won and used for the progress of all people. For space science, like nuclear science and all technology, has no conscience of its own. Whether it will become a force for good or ill depends on man, and only if the United States occupies a position of pre-eminence can we help decide whether this new ocean will be a sea of peace or a new terrifying theater of war.'



This paragraph alone merits extended discussion, because it is densely packed with ideas. We do something first and foremost 'because there is new knowledge to be gained'. When applying for a research grant in the twenty-first century, a scientist must fill out a form with all sorts of platitudes designed to mollify government departments staffed with social scientists who have invented terms like 'pathways to impact' and 'accountability'. The primary reason why we engage in science and exploration is to gain new knowledge. Knowledge is the prize. As Kennedy goes on to say, knowledge has no conscience of its own, and in a democracy, it is for society to determine how it is used. Government has a great responsibility here because investment in education is required so that people in society are equipped to make informed choices. This is harder for government to achieve than generating extra paperwork, but it would be infinitely more valuable.

Here is Kennedy later in the speech, making the explicit link between exploration and education, and carefully separating the generation of new knowledge from its potential practical uses in the service of society:

‘The growth of our science and education will be enriched by new knowledge of our universe and environment, by new techniques of learning and mapping and observation, by new tools and computers for industry, medicine, the home as well as the school. Technical institutions, such as Rice, will reap the harvest of these gains.’



Kennedy follows ‘new knowledge to be gained’ with the equally important ‘and new rights to be won...’. In his visionary and influential book *The Case For Mars*, Robert Zubrin argues that the most important outcome of the colonisation of Mars would be the development of a new branch of self-sufficient human civilisation separate from that on our home planet. Shaped by the physical, psychological and technological challenges of existence on the new frontier, and freed from Earth’s complex social and geopolitical history, the colonists could more easily circumvent the frozen ills of centuries of human folly whilst benefiting from centuries of knowledge and progress. This mixture of challenge and freedom should allow them to discover entirely new definitions of citizens’ rights and obligations and new

ways of organising society. They would build a young and exciting civilisation with a blank sheet of paper, perhaps better equipped, to paraphrase Kennedy, to ensure that the new ocean of space becomes a sea of peace.

The idea of recreating a frontier mentality may seem uniquely American, echoing the recent history of the country, but the optimism for a better future in space was also shared by the Soviets. As he climbed aboard the Vostok-K rocket on 12 April 1961 to ignite the age of human spaceflight, over a year before Kennedy's speech, Yuri Gagarin said these words:

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VOL. 51, NO. 21

CHICAGO DAILY NEWS SERVICE

HUNTSVILLE, ALABAMA, WEDNESDAY, APR. 12, 1961

ASSOCIATED PRESS — WIREPHOTO

Where Progress...

Covers The Valley!

45c PER WEEK

The Huntsville Times

'So Close, Yet So Far,' Sighs Cape U.S. Had Hoped For Own Launch

CAPE CANAVERAL, Fla. (AP) — The Redstone rocket which the United States had hoped would boost its first man into space stands on a launching pad here. The Soviet Union beat its firing date by at least two weeks.

"So close, yet so far," commented a technician who helped groom the Redstone to send one of America's astronauts on a short sub-orbital flight, hopefully late this month or early in May.

"If we hadn't had those troubles last fall and on the chimp and Little Joe shots, this year we might have made it," the technician said.

"But you have to give the Russian scientists credit. They've accomplished a remarkable breakthrough."

Dr. Hugh Deviden, deputy director of the National Aeronautics and Space Administration, told the House Space Committee in Washington Tuesday that the earliest possible date for the manned launch is about April 25.

Project Mercury officials had hoped to achieve a manned Redstone flight last December or January. A series of launch mishaps necessitated additional launchings to qualify the system.

On Nov. 6, a space capsule failed to separate from a Little Joe rocket fired from Wallops Island, Va., in a test of the escape system.

Two weeks later, a Redstone rocket because of a faulty connection which caused the escape tower to fire, leaving the rocket and capsule on the pad. This test had to be repeated before the escape system was used on a short trip Jan. 31.

An engine thrust regulator chipped the chimp shot, creating excessive thrust which led to the chimp being higher and farther than intended. Another Redstone was fired to prove out corrections made to the regulator, again delaying the manned trip.

Another setback occurred March 18 when a report of the Little Joe escape test failed. Another try is set for about April 12, when the rocket is expected to be fired.

Redstone now on the pad here is the one that was used in the May 1960 launch.

Hobbs told Egan authorities he was living in a cave in the mountains near his home north of Ft. Payne when he was killed. He stated he was in the cave when he was killed. He was killed by a bear.

The New York Times reported that the Redstone rocket was launched on April 12, 1961. The rocket was launched from Cape Canaveral, Fla.

Turn to Page 2, Column 1.



This is Russian Maj. Yuri Gagarin, history's first man in space. The Russians today rocketed him around the earth in an orbit taking slightly less than 90 minutes and brought him back safely to a prearranged spot in the Soviet Union. (AP Wirephoto via radio from Moscow)

Praise Is Heaped On Major Gagarin

First Man To Enter Space Is 27, Married, Father Of Two

LONDON (AP) — Moscow's father of a nation today, describing him as a man with "a good honest smile."

The portrait of Maj. Yuri A. Gagarin was shown and then came this broadcast comment, repeated by Moscow radio:

"For those who did not see this picture we should like to give a description of this splendid man."

On the screen appears the image of a man aged about 25-26 with a kind, Russian face, eyes set well apart, the bushy brows and high forehead.

"He wears a flying helmet, a light overall suit. His smile is good, honest smile. And there is a man of a very great and very real character. This is evident in his smile, in the intelligent, fine eyes."

Gagarin was 27 just a month ago.

He is married to Valentina Gagarina, 26, who also has a good background. She was graduated from medical school at Moscow.

They have two daughters, Yelena and Galya, just a month old.

The comment has an official background. It is a father's pride.

The party began and the flight. Gagarin was born March 8, 1934, in the village of Klushino, near Gzysk, in the Byelorussian Soviet Socialist Republic.

Turn to Page 2, Column 1.

Soviet Officer Orbits Globe In 5-Ton Ship Maximum Height Reached Reported As 188 Miles

MOSCOW (AP) — A Soviet astronaut has orbited the globe for more than an hour and returned safely to receive the plaudits of scientists and political leaders alike. Soviet announcement of the feat brought praise from President Kennedy and U. S. space experts left behind in the contest to put the first man into successful space flight.

By the Soviet account, Maj. Yuri Alekseyevich Gagarin, rode a five-ton spaceship once around the earth in an orbit taking an hour and 20 minutes. He was in the air a total of an hour and 48 minutes.

The whole sequence of events and the announcements relating to it raised a number of questions. The Soviet announcement said the flight took place today between 9:07 and 10:55 a.m., but some persons in Moscow's Western colony were skeptical that the feat actually came off today.

There was a curious sequence of events leading up to the announcement.

Rumors had been circulating several days that the space coup had been pulled off. Two days ago, Soviet TV technicians moved into the Central Telegraph Office with the evident purpose of getting pictures of correspondents in action as they reported such a story. There were various reports, none verifiable from official sources, that the flight had been made.

Then Tuesday night the Daily Worker, London Communist newspaper with apparently sound connections in Moscow, reported that the flight took place last Friday.

In splash headlines, the Daily Worker heralded "the first man in space," saying he had completed three orbits before returning to earth suffering from "after-effects of the flight."

That led to the present. About 9:30 a.m., Western correspondents were tipped off to be listening to their radios at 10 a.m. The announcement came at 10 a.m., saying the astronaut still was in orbit. At two intervals the radio broadcast messages, reportedly from him over South America and Africa.

Then came the announcement that the spaceship had been called back to earth.

Some in the Western colony expressed wonderment that the Soviet Union, with its tight control over communications, would take such a chance—announcing the flight before a successful completion.

At these snippets saw 2, the event would have turned into a disaster. The Soviet Union, in history if anything had gone wrong between 18 a.m. and the announced time of landing, 10 minutes later.

That led them back to speculation whether the London Daily Worker knew what it was talking when it said the space flight had taken place today.

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To Keep Up, U.S.A. Must Run Like Hell

VON BRAUN'S REACTION:

WERNER VON BRAUN

He Fancies A Russian Achievement

By BILL AUSTIN

OF THE STAFF

A disappointed Dr. Werner von Braun, arriving in Huntsville today, called Russia's space flight a tremendous thing and labels it the "what heared around the world."

"I'm disappointed because here again we came in as second place," he declared.

Von Braun arrived at the Huntsville airport from Grove City, Pa., where he had addressed a college group yesterday.

He said he had hoped all along the United States would be able to place an astronaut in orbit, but he said Russia has an excellent space program and they must strive to be first.

"We are going to have to run the hell to catch up," he asserted.

He also said he was convinced that the Soviet Union's first attempt to put a man in orbit, but he did not say when it would be made.

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Reds Win Running Lead In Race To Control Space

WASHINGTON, Apr. 12 (AP) — Behind the Soviet space triumph today, the United States is in a race to win the space race. The Soviet Union has won the first prize in the space race, but the United States is still in the race.

The first prize in the space race is the first man in space. The Soviet Union has won this prize. The United States is still in the race.

The second prize in the space race is the first woman in space. The Soviet Union has won this prize. The United States is still in the race.

The third prize in the space race is the first man to orbit the earth. The Soviet Union has won this prize. The United States is still in the race.

The fourth prize in the space race is the first man to land on the moon. The Soviet Union has won this prize. The United States is still in the race.

The fifth prize in the space race is the first man to return to earth. The Soviet Union has won this prize. The United States is still in the race.

The sixth prize in the space race is the first man to live in space. The Soviet Union has won this prize. The United States is still in the race.

Turn to Page 2, Column 1.

Today's Chuckle

By friendly with folks we know—of it weren't for the fact that it would be a disaster.

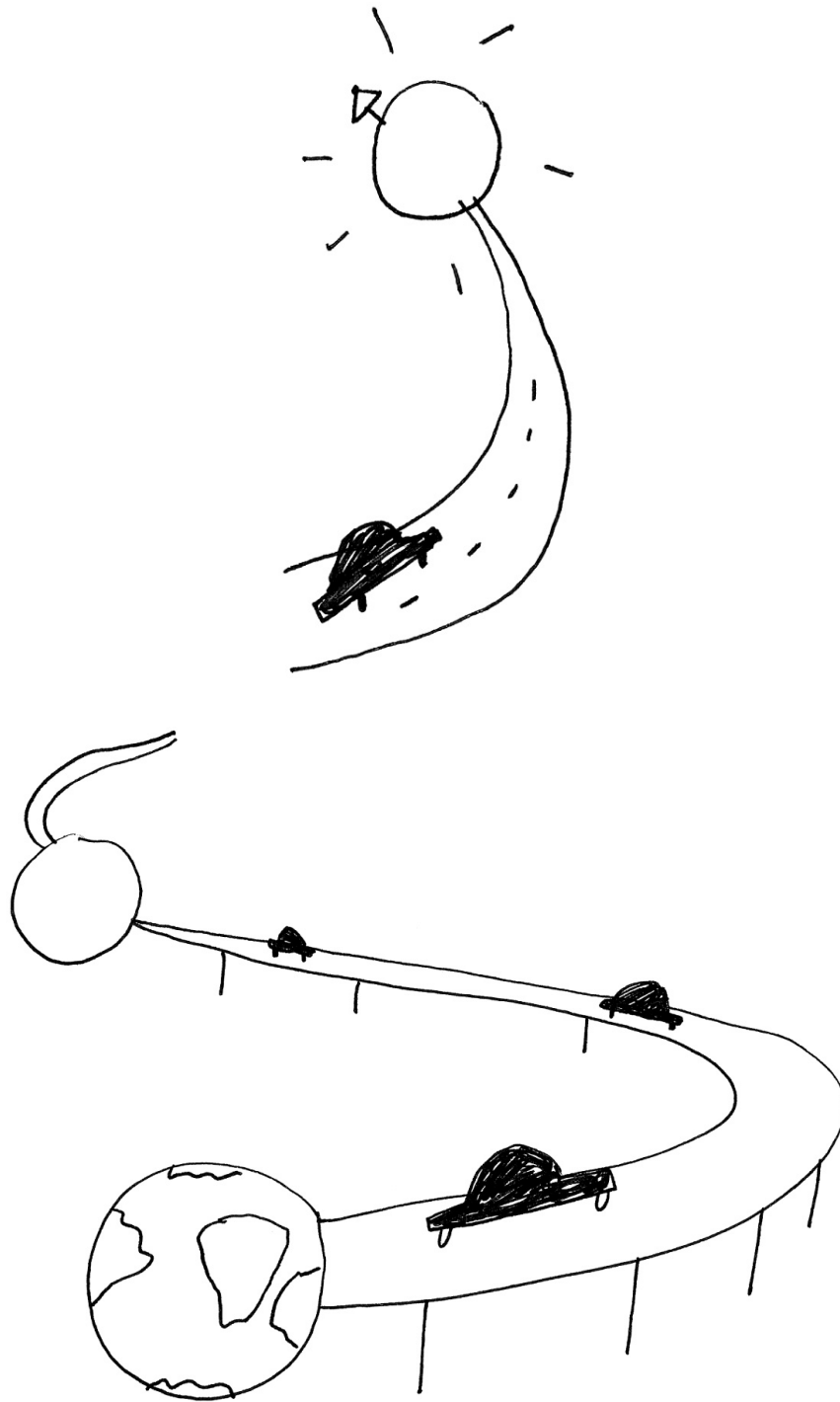
LENN JEWELL FOR

‘I don’t have to tell you what I felt when it was suggested that I should make this flight, the first in history. Was it Joy? No, it was something more than that. Pride? No, it was not just pride. I felt great happiness. To be the first to enter the Cosmos, to engage single-handedly in a duel with Nature – could anyone dream of anything greater than that? But immediately after that I thought of the tremendous responsibility I bore: to be the first to do what generations of people had dreamed of: to be the first to pave the way into space for all mankind. This responsibility is not towards one

**person, not towards a few dozen,
not towards a group. It is
responsibility towards all mankind
– towards its present and its
future.’**

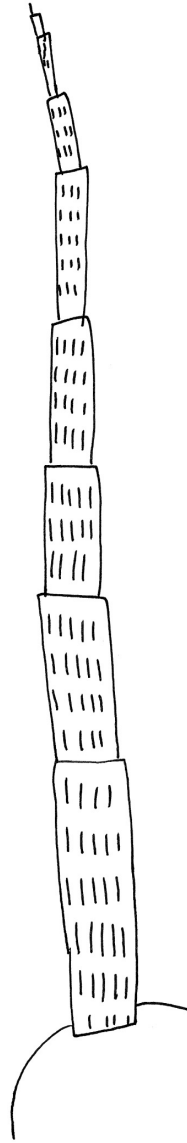
– Yuri Gagarin

Why is it that human spaceflight seems capable of generating such similar optimism and idealism in societies as different as 1960s USA and the Soviet Union and in today’s radically different democracies? Because the exploration of space is really about expansion, of knowledge, of the economy, of territory and access to resources. This might sound problematic, because in the early twenty-first century expansion has become synonymous with grotesque overconsumption leading to inequality, environmental damage and geopolitical conflict. But economic growth and the expansion of our capabilities as a civilisation are good things. I want to live in a world where everyone has access to the amount of resources I consume, the electrical power I use and the luxury of the education and health services I enjoy. I want everyone to be able to grow and develop as a human being as I have. We seem to be in a bind, but we are not. If we are careful, we see that the undesirable side-effects of growth are a consequence of our attempt to expand whilst constrained within a finite arena; the surface of the Earth. Furthermore, we see that the competition between nations for Earth’s resources, which inevitably leads to geopolitical conflict, is based on the false premise that the resources available to our global civilisation are limited. They are not.



The asteroid belt contains enough metals to build a skyscraper 8000 storeys tall and cover the Earth with it. All the precious elements and molecules we need, from water – i.e. rocket fuel – to the precious metals necessary to construct advanced electronic circuits, are waiting for us in limitless amounts. If we want to build orbiting colonies and factories or Moon and

Mars bases, we don't have to remove a single atom from the Earth. Couple this with the limitless solar energy available beyond our atmosphere and it begins to look rather silly to propose doing any heavy industry at all on Earth. This is precisely what the current generation of space entrepreneurs have realised. I recently spoke with Jeff Bezos, founder of Amazon, at his Blue Origin rocket factory in Seattle. His vision is to zone Earth as residential and light industrial, in order to protect it. We've visited every planet in the Solar System, he said, and we know with absolute certainty that this is the best one. That's why his company is called Blue Origin, after our precious blue jewel of a world. Spaceflight does not increase the pressure on our world by consuming valuable resources; it is a route to protecting our world by enabling us to grow into a richer and more interesting civilisation whilst simultaneously consuming less of Earth.



Imagine a world where there is no conflict for resources because resources are effectively infinite. Imagine a world where there is more than enough to go around, not because some of us become more frugal, but because all of us have access to whatever we desire. What would that world be like? It would be an interesting world because we'd be forced to focus on the questions that arise when the challenge of mere existence is removed. What's the point of life if living itself isn't a struggle or competition? The point is, as Kennedy told us at the beginning, to set sail on this new sea 'because there is new knowledge to be gained, and new rights to be won, and they must be won and used for the progress of all people'.

**This is why
we should go
into space.**

Now.



‘SPACE THE FINAL FRONTIER...’

The next generation



For three generations, the most vivid imagining of our future in space has been the liberal Utopia created by Gene Roddenberry for *Star Trek* and its offspring and ancestors. Here was cultural diversity, perhaps more with extraterrestrials than humans, though good intentions were there from the start. A human race that, despite historical evidence, usually arrived on other planets keen to befriend and learn rather than plunder and destroy for a quick buck, leaving a random husk of alien lifeforms destroyed by measles and space hooch.

It was the ‘final frontier’ claim that now seems bigger than ever before. It was as if almost everything had been done. ‘Well, we’ve done Utah and Arizona, all that’s left are these billions of galaxies with billions of stars in them, perhaps we can pop up a few casinos?’

When Patrick Stewart joined a *Monkey Cage* panel, he told us that he was not keen on the idea of space exploration before he made *Star Trek: The Next Generation*...

‘... because the evidence from our own planet is that every time we’ve explored another world we’ve ruined it. And then I was offered Star Trek and so it was not the done thing to say that kind of thing.’

Series 7, Episode 1 (19 November 2012)



When the original series of *Star Trek* began, we hadn't yet touched down on the Moon, yet it was imagined we would be much further on with space exploration than we are now. We know more about the Moon than we know about our oceans, and we're getting there with Mars, with increasingly vivid images of its surface, but for a few decades, investment slowed. The excitement of space subsided, our ambition shrank.



Once the space race, or the Moon race, had been won, extraterrestrial endeavour moved further and further away from the front page. Many people believe that Apollo 11 was the only trip to the Moon. Once

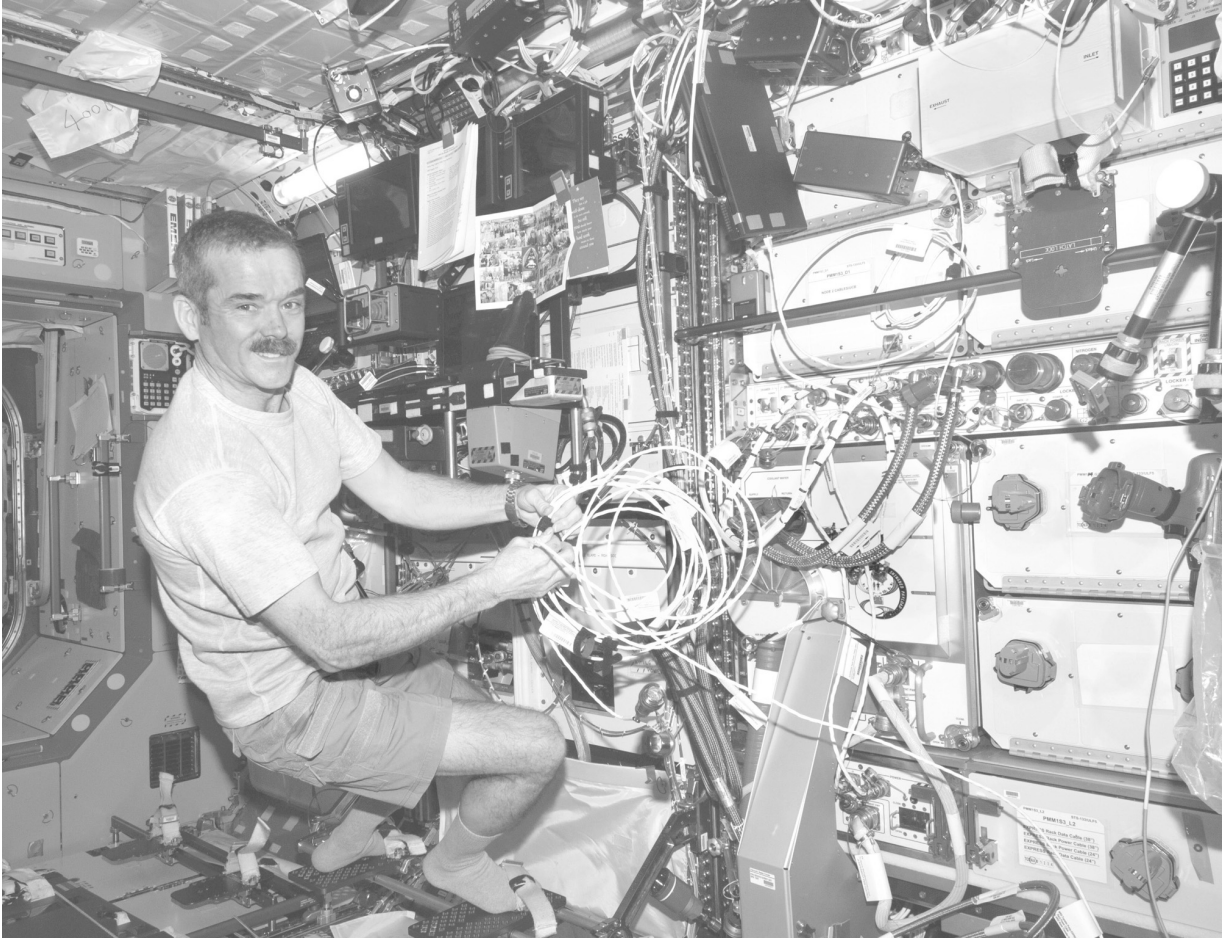
Armstrong and Aldrin left their footprint, there was no return, though Tom Hanks gave it a go.

How many Apollo astronauts can you name? Alan Bean? Charlie Duke? What about the first woman in space? When so much tittle-tattle and kiss and tell makes the news, why are our adventures in space of so little mainstream journalistic interest? Do we have to make a TV reality show where aggressive narcissists are voted to be ejected out of the air lock week by week to make people sit up and pay attention? You are far more likely to see an actor who has recently pretended to be an astronaut for Hollywood on a TV chat show than an actual astronaut. This is also true of mathematicians and physicists: 'tell me, Benedict, what was it like pretending you were a mathematician?' We seem keener on those who pretend to explore than those who actually explore.

Maybe we are strange and old, but we think when you have a human who has been on the Moon or spent 200 days in space, they should be TV primetime. We saw a little of the Hollywood over science psychology when Patrick Stewart and Professor Monica Grady were on one of our space exploration episodes.

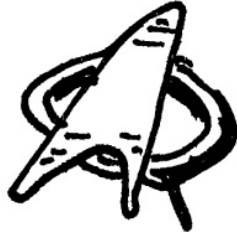
Monica Grady, Professor of Planetary and Space Sciences at the Open University, held up a piece of a meteorite. The weight takes one by surprise, it feels denser in the hand than the rocks of Earth. It was 4.6 billion years old, dated using isotopes. The audience were interested, but not nearly as interested as when Patrick Stewart went into his top pocket and revealed his communicator badge. Gasps, cheers, oohs and ahhs, particularly from Brian Cox.





Astronaut Chris Hadfield was onboard the International Space Station in 2012 and 2013 as part of Expedition 34 and Expedition 35, and served as ISS commander during Expedition 35.

Robin: We have talked about some of the most incredible, mind-blowing ideas of evolution, of particle physics, and then something made by a prop manufacturer in a suburb of LA. Can you believe it?!



But the reprimand was to no avail, the meteorite was cool, but it hadn't been on telly nearly as much as the communicator badge.

Recently we have seen a new elevation of the astronaut as attraction. Canadian astronaut Chris Hadfield has been a great space exploration diplomat. His short films of life in the International Space Station, covering everything from crying in space to making burritos, captured the imagination of a new generation and rekindled the imagination of older ones. His final despatch from the ISS was a cover of David Bowie's *Space Oddity*. On its original release, it was an almost novelty single, riding the crest of the space fascination in late 1960s popular culture. It repaid that debt by catapulting Chris Hadfield into the orbit of space celebrity, with his zero gravity tribute. Commander Hadfield's ability to translate the physical, scientific and emotional experiences of journeying into and living in space has been informative and enlightening and has seen queues form around the block at bookshops.

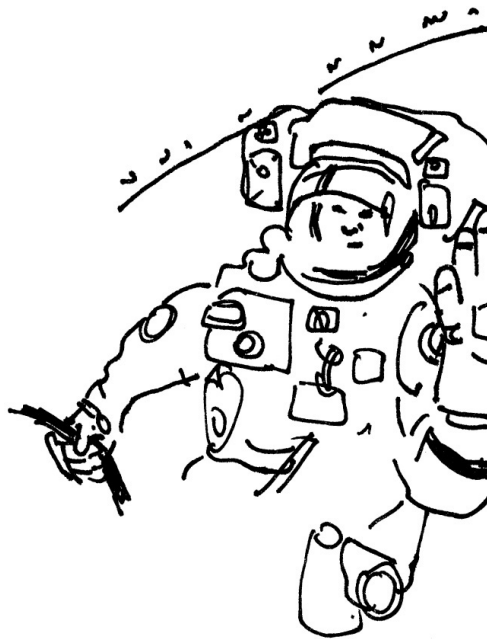


His story is one of tenacity. A child sees the first Moon landing, and from then on every day he goes to school thinking, 'what must I do today to ensure that I can maximise the chance that I may go into space, even though I am aware the chances of that are slim?'

We have been fortunate to stand on stage with Chris as he explains every stage of thought as you travel from the Earth's surface and through its atmosphere to the point of docking with the ISS.

'When you look out of the window, it feels like there is a great awe-inspiring presence. Just the omnipresence of the world, the rareness of it. There is a hushed respect for what is happening and you will float silent next to someone else and just occasionally murmur something about what a spectacular sight our world is.'

Christmas Special (25 December 2014)



All thoughts of follow-up questions vanish as he tells you about how he held on to something akin to a luggage strap on the outside of the ISS, looking down on the planet below him.

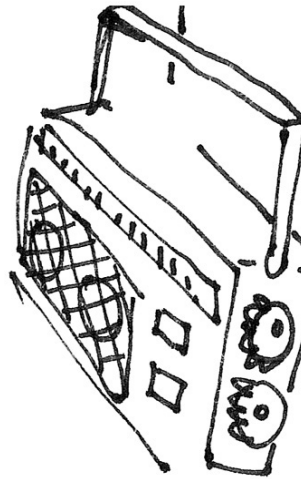
It appears that going into space, being one of the rare humans to see the entirety of your home planet in your field of vision, gives you a new perspective on its fragility, a perspective sadly lacking in much modern political discourse and petty feuding.

British astronaut Tim Peake has further enthralled the population of the United Kingdom with his stay on the ISS. Though we may like to

encourage imagining a world without borders, people still gain an additional thrill when they share nationality with the latest human above us. Sadly, Tim Peake's hectic schedule as an ambassador for space exploration has meant we have been unable to secure him for a *Monkey Cage* so far, though we have embroiled him in a Cosmic song and dance spectacular written by Eric Idle.



We have been fortunate to have one episode of the radio show that featured an all-astronaut panel. Charlie Duke (Apollo 16) told us he found it hard to sleep the day before he went to the Moon, and we found it hard to sleep the day before meeting someone who had been to the Moon.



There is a surge of optimism when you spend time with astronauts. It is a reminder of what human ingenuity can do. It is a reminder of positive ambition. It is also a reminder of the importance of Velcro in zero gravity. Claude Nicollier, Swiss astronaut, veteran of four space-flight missions, described it as the most vital necessity, otherwise you have got everything floating about all over the place.

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‘Gordon’s alive. And dead. He’s in a superposition.’

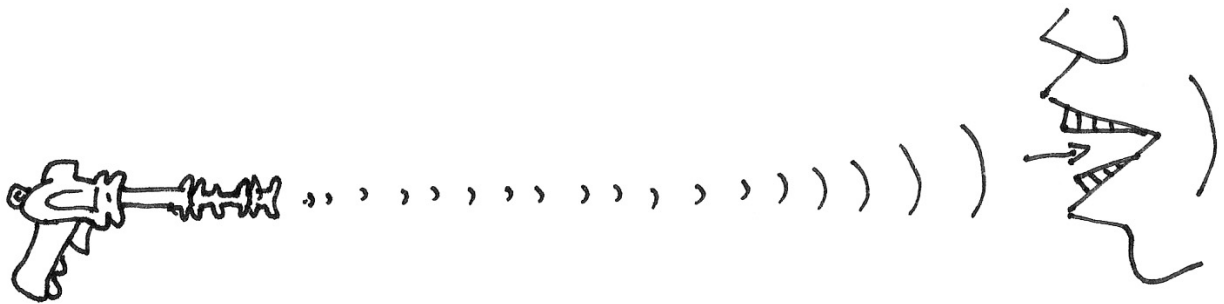
Brian Blessed, Series 8, Episode 3 (8 August 2013)

One of the strongest advocates of space travel is the magnificently powerful and linguistically pugilistic actor, Brian Blessed. When he appeared on the *Monkey Cage* at 79 years old, he had not given up hope of reaching space. He has been wanting to go to Mars since he was six years old and had seen an image of it in a picture book:

‘We are the children of stardust, and I want to get out there. I’m determined to go to Mars and beyond.’

If all the cheerleaders for Mars had been as powerfully Shakespearian as Brian B, maybe we'd be there by now. Blessed is the sort of explorer who considers the use of oxygen tanks when ascending Everest as a cop out. When he says he doesn't think it counts if you use oxygen, you can't be certain whether he's talking about tanks, or actually suggesting you should hold your breath all the way up to the summit. In his words,

'To blow with all cosmic rays. I'd eat them!'

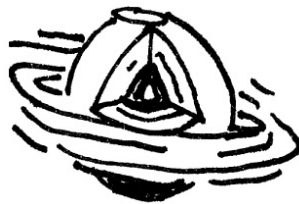


In late middle age, Brian did cosmonaut training. He went up to 11G on the centrifuge machine 'on this little machine on a little chair. Russians had managed only 50 seconds on this. I managed 75 seconds, which Kevin [Fong]³ said was unwise.'

Blessed definitely has the right stuff, though he may have been the wrong shape for an astronaut. Sadly, being neither American nor Russian, he never got his chance during the space race.

'I think the greatest danger in life is not taking the adventure.'

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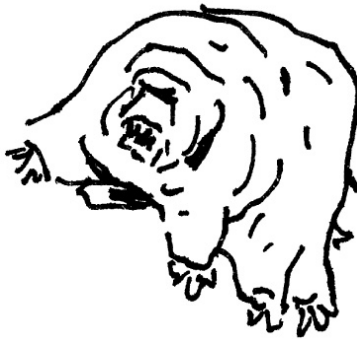


There have been disagreements on *Monkey Cage*, occasional fiery exchanges, but they are usually doused by the cool-headedness that accompanies an exchange of differing differential equations. The most

volatile exchange we've seen was on the topic of the most likely places to find life beyond our planet, and featured planetary scientists Carolyn Porco and Monica Grady. Carolyn Porco saw one of Saturn's moons, Enceladus, as the prime location for microbial life, but Monica Grady felt the caves of Mars might be the place.

Monica: It's quicker and cheaper to get to Mars than it is to get to Saturn.

Carolyn: I know, but you guys are going to be digging for eons, and we are going to come back with the microbe.



Monica: But we can send people to Mars eventually.

Robin: Hey you two, just calm down.

Series 11, Episode 3 (2 February 2015)

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Should we continue to send humans into space? Should we keep reaching further and further away when we have so many problems close to home? The pioneering poet Gil Scott-Heron wrote 'Whitey on the Moon', a harshly critical view of the journey of white heroes to the Moon while so many of the black underclass languished in rat-infested slums. Does this change with the stories of Katherine Johnson, Dorothy Vaughan and Mary Jackson, three pioneering African-American mathematicians whose calculations were hugely important to landing humans on the Moon? Why don't we just send robots into space? Do ideas of colonising Mars give us false hope? Or is the cost of such endeavours handsomely repaid by the ability they have to show us a vision of possibilities beyond our petty feuds?

Is the liberal idyll of a *Star Trek* future a real possibility, or at least a dream worth having, to dilute the pessimism that can condense into a fog of inaction?

As Sandra Magnus, who has spent 134 days on the ISS, told us:

'When people ask us why, we start to talk about how and what. The why is, I think, quite fundamental. We are curious as human beings. We are explorers as human beings, and I think it comes down to something that simple. It's a natural curiosity that makes us unique.'

Series 16, Episode 2 (10 February 2017)

Claude Nicollier, who led the renowned spacewalk that involved repairs and updates to the Hubble Telescope, sees it as a vital evolutionary step.



‘I see human access to space as Darwinian evolution. This is a step in the evolution of humans that will lead us to a situation where we have a better survival possibility, long term. When life left water 300 million years ago, this was a biological necessity. Going to space is a biological necessity – we can’t avoid it.’



Astronaut Jeffrey A. Hoffman, in December 1993, signals directions to European Space Agency astronaut Claude Nicollier (out of frame), as the latter controls the Canadarm during the third of five spacewalks on the Hubble Space Telescope servicing mission.

In the end, is it as simple as we must do it because we can do it and what a waste of civilisation if we

don't keep moving further and higher?

CONSPIRACY THEORIES

So you want to be punched by an astronaut?



On the day on which Neil Armstrong died, there was a harvest moon above the River Thames.

It was a coincidence, but a charming one. It was as if the Moon was paying its respects. Going online, I wondered how soon I would see people declare that 82-year-old Armstrong had been assassinated because he was about to reveal the truth about the Moon landings.

I was way behind the times; apparently that hot-headed rumour began at the moment of the death announcement. *Capricorn One* has much to answer for.⁴

If you have a hankering to be punched by an Apollo astronaut, a good way of achieving this is to approach them and say, 'so which studio did you film the Moon landings in?' Have you been furious when a roommate or relative has accused you of not doing the washing-up or taking out the rubbish when you did, you definitely did? Now imagine going all the way to the Moon and having complete strangers come up to you and say they don't believe you did it. Buzz Aldrin, at 87, is still your best bet for a sucker punch.

Considering the exceptional speed of development in human flight, the ease with which we can fly around the world, and the ability that we have to observe the International Space Station from the ground, why are there still people who refuse to believe that human beings have stood on the Moon? Is it about a sense of superiority that comes with believing you rise above the herd by not falling for the 'they put a man on the Moon' baloney?

What is peculiar is how often they decided to fake it. Not just Apollo 11, they kept going back to that Moon studio in Burbank even when the public was losing interest. Usually in LA, a show is cancelled mid-run in those situations. They even faked one of their missions – Apollo 13 – going wrong.

Conspiracy theories have been updated over time to skirt around awkward evidence-based questions and answers. Some theorists now say that humans did land on the Moon, just not the astronauts that were presented to us.

You can read that Armstrong, Aldrin, Duke, Bean and the rest are fronts for the men who got to the Moon but died up there, fatally irradiated or consumed by carnivorous Clangers. The tale of the unknown astronauts seems to have been added so that the hoaxers don't have to deal with the awkward fact that there are retroreflectors that were placed on the Moon during three of the Apollo missions.

Some theorists suggest that the Apollo mission was faked in a studio under the direction of Stanley Kubrick, but looking at the increasing duration of his movies from preplanning to completion, it is highly unlikely he would have made the deadline. Apparently, when we did land on the Moon, Kubrick was annoyed to see that the design of the Moon surface used for *2001: A Space Odyssey*, something he had spent much time contemplating, was not as accurate as he would have liked.

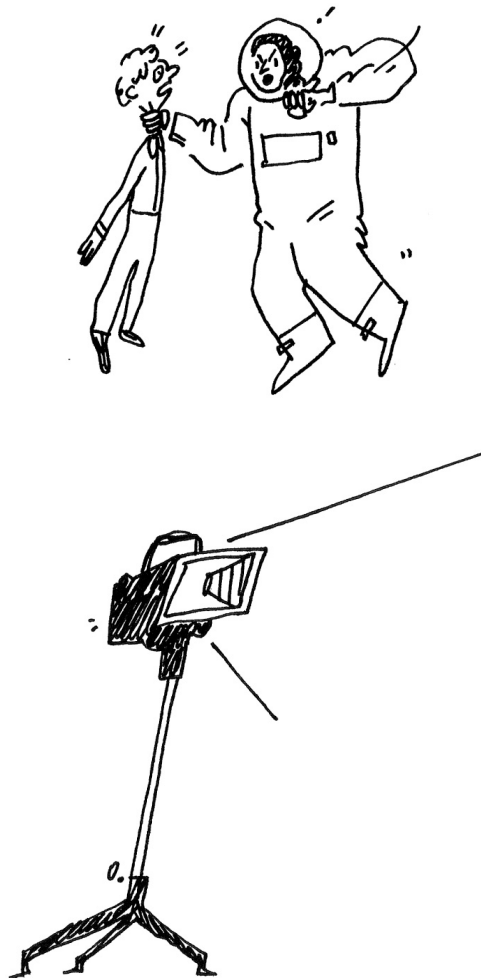
Hoax ideas can be so elaborate that you can even persuade some that the Apollo missions were actually holograms projected from state-of-the-art equipment placed on Mars.

'Evidence' against the Moon landings include the appearance of studio lights on the rockscape, though others may well consider that to be nothing more than lens flare. Lens flare can also be used as evidence of ghosts, so, in the choose-your-own-adventure game of belief you can have:

A. Lens flare is commonplace, and after all, you would imagine that after NASA had gone to all that effort of faking the Moon landing, they'd have someone to check on which studio lights might be in shot.

B. It must be studio lights, there can be NO OTHER explanation.

C. There are ghosts on the Moon.



Another question popular with hoaxers is the movement of the implanted flag. Official explanation is that the momentum and inertia of the Moon, the wobble as the flag was placed in the ground, and overly zealous unfolding of the rods all created ripples. But what if it was because actually it was all filmed in a windy studio?

Mind you, I have seen lots of films, and usually they remember to close the studio doors and don't allow a through draught...



Why are there no stars visible? The quickest answer is that the strength of light being reflected off the Moon means that the light of stars is not picked up on film, but maybe NASA just forgot to add stars, which might be a reason why the BBC added stars to *2001: A Space Odyssey* when it was first put on TV, much to the fury of science-fiction fans everywhere. It is hard to know what the public want – no stars, some stars, too many stars?

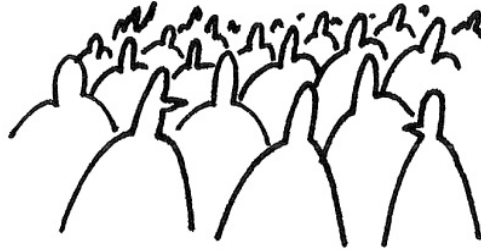


Other answers you might need are 'no, they had cameras in the chests of their spacesuits', and 'no, you see the powder on the surface is very fine'.

For some people, the Moon landing hoax is only a distraction from the big hoax, the Moon itself.

Popular gurus of thrilling gobbledegook are still peddling the theory offered in Don Wilson's *Our Mysterious Spaceship Moon* that our moon is a hollowed-out spaceship sent by aliens to monitor our prehistory.





Back on planet Earth, Oxford University physicist David Grimes published a study a few years ago that created a mathematical way to work out the likelihood that a conspiracy could remain secret based on the number of people involved in the plot. The more people involved, the less likely that clever Burbank Moon studio could have remained secret. For a hoax to last five years, Grimes calculated that the maximum number of plotters can be no more than 2521; you need to go down to 1000 to last a decade and 125 if you want your hoax to last a century. Based on the starting point of the Moon hoax as 1965, and the number of employees at NASA being 411,000 (therefore the maximum number of people, in his equation, who could be involved), Grimes's equation reveals that a hoax would have been uncovered after 3 years and 8 months, making the likelihood of conspiracies such as the faked moon landings as being 'eye-wateringly unlikely'. Somewhat optimistically, he went on to say that he hoped that the figures might persuade some people to 'reconsider their anti-science beliefs'.

But why let a few facts and figures get in the way of a good conspiracy? Conspiracy theories allow us to feel smart without having to actually really put in the effort of deep understanding. It is far easier to understand a book of Moon conspiracy than understand the equations, engineering and technology required to reach the Moon. It allows us to feel like the smartest guy in the room. It allows someone to know next to nothing but believe the one thing they do know overturns everything else. It gives the theorist an instantaneous high horse that means they can proudly look down on the experts.

We don't like being ignorant, but learning everything takes ages. A shortcut is to overturn all ideas of expertise and reality that get in your way. Then again, I would write this, I'm probably one of the illuminati. Now where's

my sacred owl and what's Henry Kissinger done with the sacrificial bathrobes?

PHONE HOME

The search for ET

The search for and possibility of extraterrestrial life has been a frequent topic on *Monkey Cage*, first discussed on the second episode of the first series. Seth Shostak, from the SETI Institute (the Search for Extraterrestrial Intelligence), the organisation that searches for radio signals of intelligent origin, told us how scientists search the skies systematically for evidence of alien life, and Jon Ronson told us how Robbie Williams' assignations in the American desert were a contribution to this effort, in his signature, rakish way.

Jon Ronson: If aliens live among us, why do they always reveal themselves in ambiguous ways?

Seth Shostak: I agree, if they were here, the evidence would not be ambiguous. The Spaniards when they sailed to the Americas, they didn't just sit three miles off the coast teasing the Native Americans 'are we being invaded, or not?' There was no doubt.

Series 1, Episode 2 (7 December 2009)



Science-fiction writers have frequently suggested that the only thing that will save us from our apparent propensity to annihilate ourselves over petty squabbles will be a threat of despots from beyond planet Earth.

Our petty tribal differences would be set aside should we find ourselves confronted by an alien invasion. It is, of course, likely that there would be sly collaborators and sneaky appeasers, but a vast gleaming fleet of ETs could be just what we need to join hands and sing ‘Kumbaya’ while plotting our sneaky attack. Or we could just set our differences aside anyway.

They may come in peace, as imagined in *The Day the Earth Stood Still* and *Arrival*, but that might not prevent us uniting to create outer atmosphere merry havoc. How would we react to finding out that the Earth is unique or special when it comes to planets capable of spawning complex life? How would we deal with discovering that we are not the smartest thing in the Universe, maybe not even the smartest thing in the neighbourhood?

During the twentieth century, there have been boom times for alien visitations and abductions.

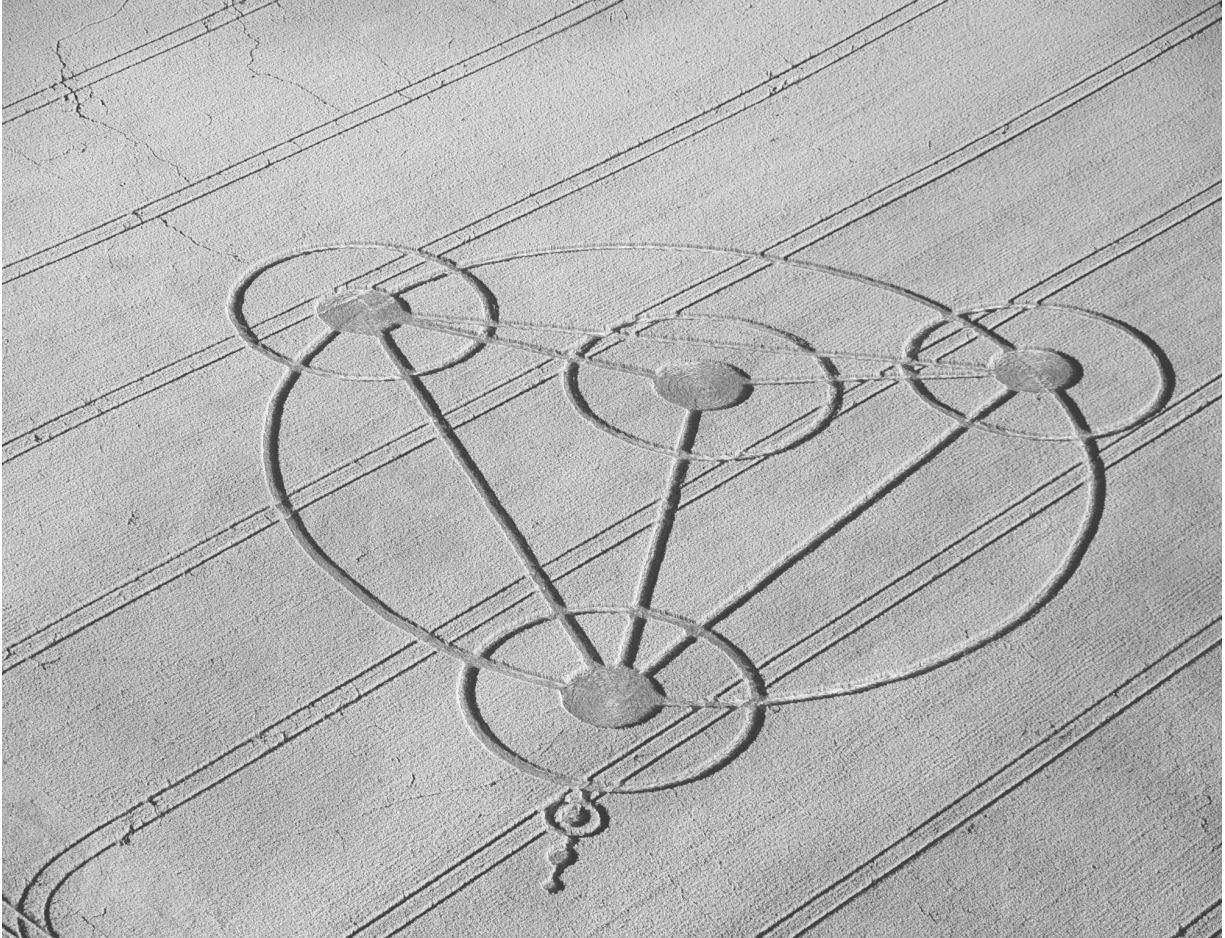
The fifties saw flying saucers grazing the skies and a plethora of bleary hubcaps debated over.

Alien abduction cases continued to pop up in the sixties, seventies and beyond, interest being sustained by Whitley Strieber's best-selling book *Communion* – a 'true story' of his encounters with aliens. And there was *The X-Files*, probably the only good to come of any of it.

Crop circles were an aesthetically pleasing conundrum that reached a pinnacle of intrigue and fascination in the 1990s. Were aliens leaving elaborate patterns like wheat-field doilies as a message, or was it extra-terrestrial graffiti on something they considered to be little more than a shunting yard siding of the galaxy? Or was it two men with planks, possibly called Doug Bower and Dave Chorley?

Popular UFO sightings in the early twenty-first century have included observations of two beacons of light moving peculiarly in tandem, which coincided with (but were unrelated to) a boom in the sales of Chinese lanterns that came in packs of two and can be observed to travel in a spooky pattern highly suggestive of questions such as 'are the crepe-paper aliens coming for us?'





Personally, we think it is highly unlikely that any of the observations of potential alien activity are caused by actual extraterrestrial activity. They are more likely to be examples of known natural phenomena such as sleep paralysis, wandering

imaginations, pattern-seeking minds stimulated by pop culture imagery, or the ingenuity of attention- or cash-seeking hoaxers.

Why do we take this view? After all, the apparent failure to be visited by aliens tells us little about the likelihood of life beyond Earth. We are a small planet in a big galaxy. The Milky Way is made up of between two and four hundred billion stars, many of which have planetary systems around them. Current estimates suggest that at least one in ten of the stars in the sky has at least one rocky, Earth-like planet orbiting inside the habitable zone around the star, which means that temperatures on the surface could allow for the existence of oceans of water. That's at least 20 billion potential homes for life. And life may not be confined to planets. Even within our own solar system, moons such as Saturn's Enceladus and Jupiter's Europa appear to have liquid water lakes or oceans below their surfaces, and may be habitable. Mars also offers hope for alien hunters, because there is strong evidence that the conditions to support life were present in the past, and may still be present sub-surface today.

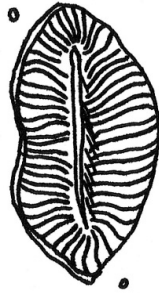


If life does exist on Mars or deep in the oceans of the Solar System's moons, it will be simple life, almost certainly single-celled and definitely not intelligent. When we speak of aliens, though, we usually mean the pilots of spacecraft. Two questions arise: firstly, what is the probability that life will begin on a planet or moon? And secondly, what is the probability that this life will end up creating a spacefaring civilisation?

The answers to both these questions are, strictly, we don't know because we have a sample size of one: the Earth. The history of life on Earth may, however, offer clues that allow us to make an educated guess as to the probability of intelligent aliens existing nearby.

The first observation is positive. Life on Earth began pretty much as soon as it could after the Earth cooled down and the oceans formed. There is good evidence of life around 3.5 billion years ago in the form of 'microbially induced sedimentary structures' discovered in Western Australia in 2013. These structures were found in a rock layer laid down during the Archaean period 3.48 billion years ago. There is also evidence of biological activity in the 3.7-billion-year-old Isua Supracrustal Belt in Western Greenland. Scientists studied the ratio of carbon isotopes and found an increased percentage of carbon-12 above the 98.9 per cent expected to be present naturally in the environment. Life prefers to use carbon-12 over the rarer and heavier carbon-13 isotope, and therefore an enhanced amount of carbon-12 is taken to be a signature of biological activity. Many biologists argue that the rapid emergence of biochemistry from the geochemistry of the young Earth has a sense of inevitability about it, and that one might expect self-replicating carbon molecules that can transmit information from generation to generation to emerge wherever the conditions are right. As we mentioned above, the necessary conditions appear to be water in contact with rock and geological activity, and these are almost certainly common within our solar system, never mind elsewhere in the Universe. We might therefore expect the Universe to be teeming with life.





The second observation is negative. Even if this rough and ready guess about the ubiquitous nature of life in the Cosmos is correct, the step from the origin of life on Earth to complex, multicellular organisms took a very long time indeed. The first evidence of multicellular life on Earth are the fossils of the so-called Ediacaran biota, dated at around 650 million years old. Large numbers of complex fossils appear during the Cambrian period 530 million years ago. This implies that, as far as we can tell, life on Earth remained single-celled for over 3 billion years after its origin, and only took the first steps towards intelligence in the last 600 million years. Three billion years is a very long time to wait – a quarter of the age of the Universe. Why did it take so long? A possible answer can be found by considering the origin of the cell type out of which ALL multicellular life on Earth is constructed – the eukaryote. Eukaryotic cells have a nucleus and a host of specialist structures, such as mitochondria, which perform dedicated functions in the cell.



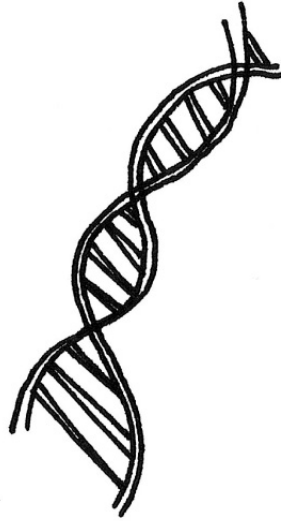


Single-celled organisms such as bacteria are a different cell type, known as prokaryotes. Prokaryotic cells have no nucleus and are much simpler in structure.

The early cells many billions of years ago were prokaryotes, and so the question arises, how did the prokaryotic cell evolve into the eukaryote?


The most widely accepted answer, known as the Fateful Encounter Hypothesis, may hold the key to understanding why it took so long for multicellular life to evolve on Earth.

One day, in one place in a primordial ocean, a prokaryote known as an archeon – a type of single-celled organism still living on Earth today – somehow engulfed a bacterium and survived. Even more surprisingly, the new archeon, complete with symbiont bacteria, managed to reproduce with the symbiotic relationship intact. This is almost unbelievable, but we believe it happened because the clues are in your cells, and in the cells of every other multicellular organism on the planet. The mitochondria inside your cells, the structures that provide the power to your body through the synthesis of ATP, are certainly bacterial in origin. They even have their own loops of DNA that do not participate in sexual reproduction and are passed unaltered down the maternal line. There are also traces of archeon DNA in your cells, an echo of the distant ancestral host. The suggestion is that the mitochondria are the highly-evolved remains of the first bacterial symbiont that entered the archeon so long ago. If this is correct, then we all – every tree, insect, blade of grass and human being – owe our existence to a *single chance event* that occurred over a billion years ago in the primordial oceans of ancient Earth. If the fateful encounter had not occurred, there would be no complex life on Earth today.



The story of the unlikely origin of complex life raises the distinct possibility that, while the Universe may be awash with single-celled lifeforms, the emergence of complex multicellular life may have been a freak accident. This staggering possibility leaves that distinctive sickly feeling when one steps out obliviously into the road and is tapped gently by the wing mirror of a ten-ton truck. Our existence seems almost impossibly contingent on the unlikely survival of a bizarre chimera.

We don't know whether this is the only path to intelligence, or whether it is likely or unlikely, but it is at least plausible that we are very rare and therefore we are very very precious natural structures. That is certainly not an argument to give up on the search for others, because the question of our solitude is one we surely must strive to answer.



Seth Shostak returned to talk about the search for alien intelligence when we recorded a show in San Francisco with planetary scientist Carolyn Porco and comedians Paul Provenza and Greg Proops.

Carolyn Porco: In our own solar system you are looking for microbial life. Looking in the places where we might have microbes. Looking for water, simple amino acids [found in meteorites] and the basic elements – organic materials.

Greg Proops: If you want to go to a cold inhospitable world where there are only protoplasmic microbes and no suggestion of intelligence or sensitivity, you can come to a meeting with me in Hollywood any day that you like.

Series 12, Episode 4 (27 July 2015)



Perhaps we are alone. Perhaps the Universe is teeming with life so intelligent that it has taken the decision not to signal anyone else and stay snug and safe on their own planets.

Is it melancholy to imagine that many forms of intelligent life will evolve in our universe, but that the windows of intelligence and ability to communicate across vast expanses never coincide? By the time we receive a message sent from millions of light years away, we are aware that their nearby star may have long since exploded. For those that gain the ability to travel vast distances in a lifetime, their holiday jaunts may be like visiting a thousand National Trust properties, each one a planet with a few remnants of jutting foundations and turrets, an occasional mosaic showing a lizard-like empress and clues to a diet in a fossilised poo.



Or, when we look out into the night sky and allow our imaginations to wander outwards to those twinkling diamonds in the dark, are we contemplating only slime?

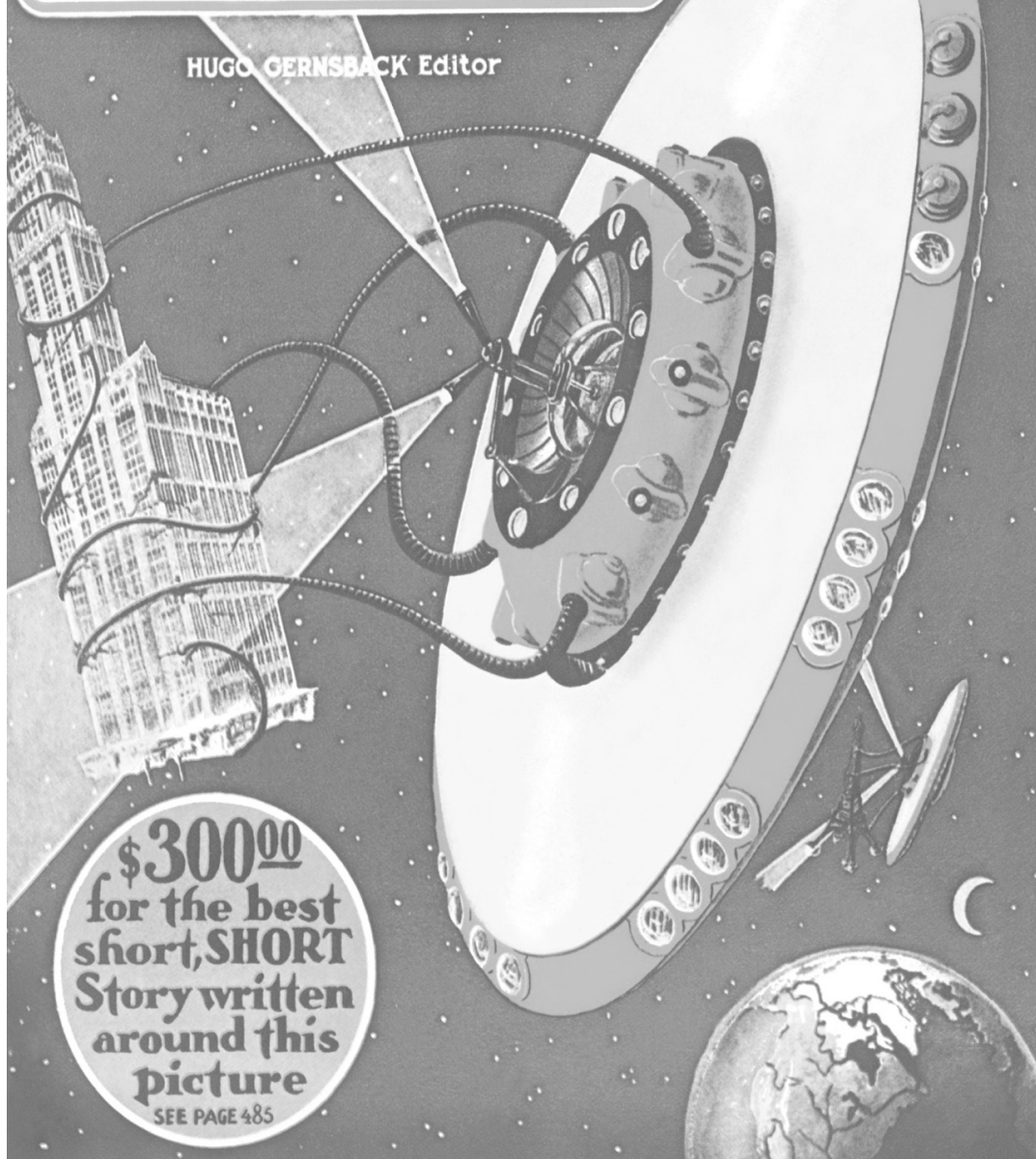


Science **WONDER** Stories

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SCIENCE FICTION v SCIENCE FACT

‘Science should not outweigh the comedy!’

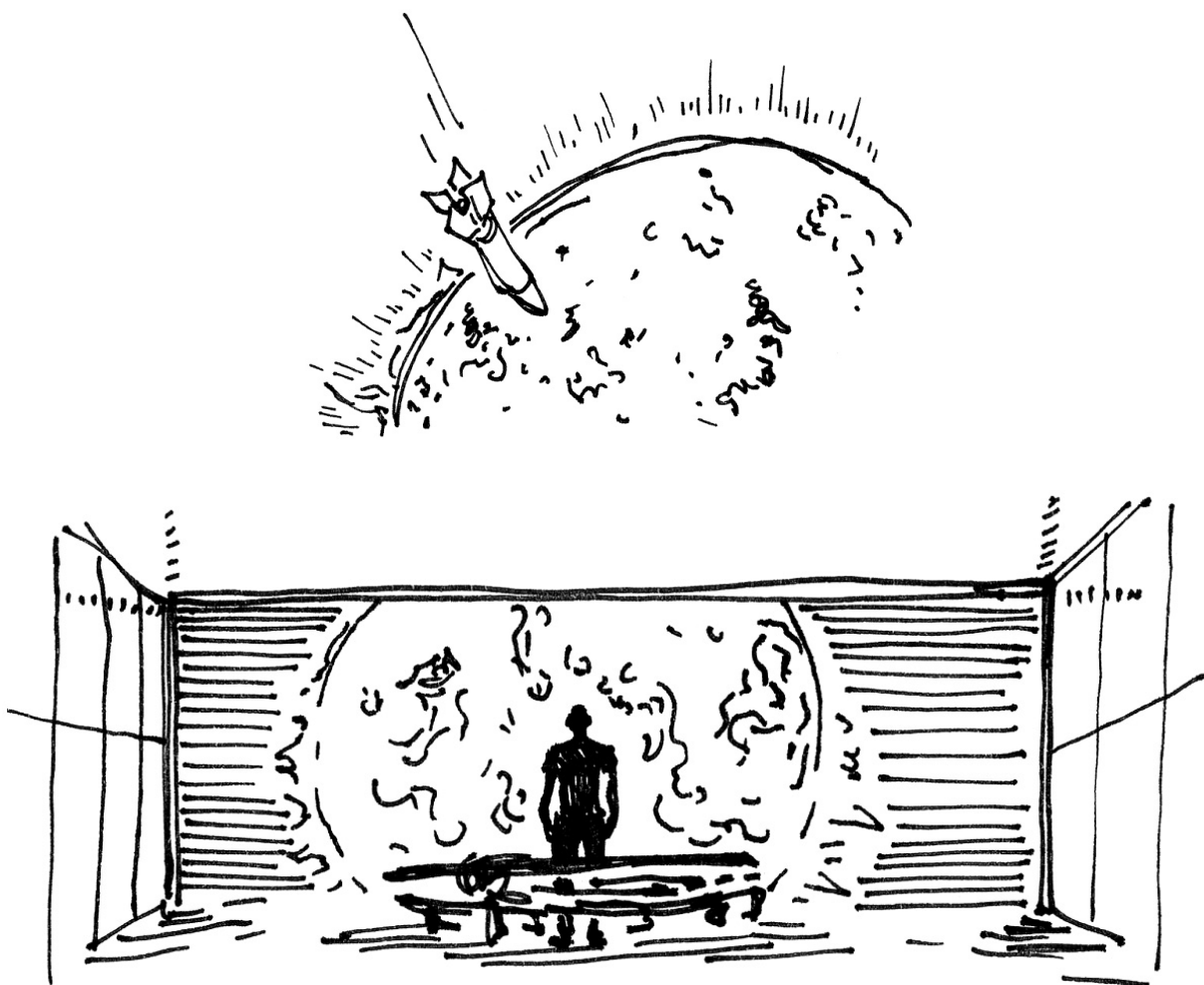
*David X. Cohen (writer and producer of The Simpsons and Futurama),
Series 12, Episode 2 (13 July 2015)*

ROBIN: For many of us, it was the excitement of science fiction that attracted us to science fact. The TARDIS may break the laws of physics by going back in time to events inside our past light cones, but the adventures and ideas that it implants can pleasantly disturb us into thoughts of spacetime and relativity from behind the sofa. Douglas Adams’ *Hitchhiker* books are many people’s introduction to the idea of living in a probabilistic universe. Philip K. Dick perplexes us into thinking about the nature of reality, what it is to be self-aware and when we might consider a robot should be granted human rights.

In the past, science-fiction movies have frequently had scant regard for science.

BRIAN: Quite right, Robin. The writing often rides roughshod over the relativistic realities of space travel, the impracticality of hand-held, light-based weaponry and the teleportation of macroscopic objects. There are countless examples of diabolical galaxy-straddling plot twists born of ill-considered ideas which violate not only science but common sense, all in the name of creating a starry picture show.

R: I know of one physicist who was advisor on a film where the core idea was that sending a bomb into the Sun could restart it. What a load of nonsense!



B: Erm, yes. Robin is referring to the film *Sunshine*, on which I was the science advisor. The film is an allegory of our struggle to retain our humanity in the face of the overwhelming power of nature and the dawning realisation of our physical and temporal insignificance. The Sun is a god, and it will drive us insane if we approach it unprepared. The physicist, played superbly by Cillian Murphy, avoids madness by approaching the divine clad in the armour of reason. The Solar physics is a MacGuffin, and as such I let it pass in the service of a significantly deeper message.

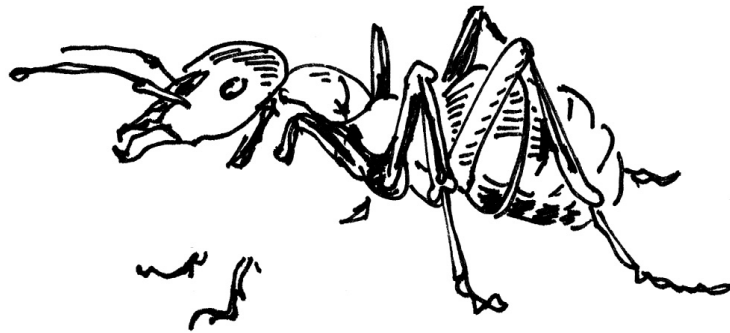
Okay. That'll do. Dodged that one. (Obviously don't print this line in the book...)

R: Science used to be an excuse to make tarantulas the size of a house or to have laser battles on Mars. It offered the pretence of modernity; no longer

cowboys pistol fighting around rocky outcrops in Monument Valley, but spacemen duelling on the rocky outcrops of a distant planet.

With the dawn of the nuclear age, radiation became the reason for the creation of monsters, superpowers and catastrophes. *The Incredible Shrinking Man* did exactly what the poster suggested. *Them!* was the story of ants mutating to voracious massiveness due to nuclear testing in Mexico. *The Day The Earth Caught Fire* saw our planet spinning towards the Sun after nuclear tests at the South Pole and North Pole coincided and deflected our planet from its orbit.

Before you start worrying too much, let's check with Brian on these as scientific possibilities.



Let's start with the giant ants, isn't there a point where the structure of an ant is no longer viable beyond a certain size?

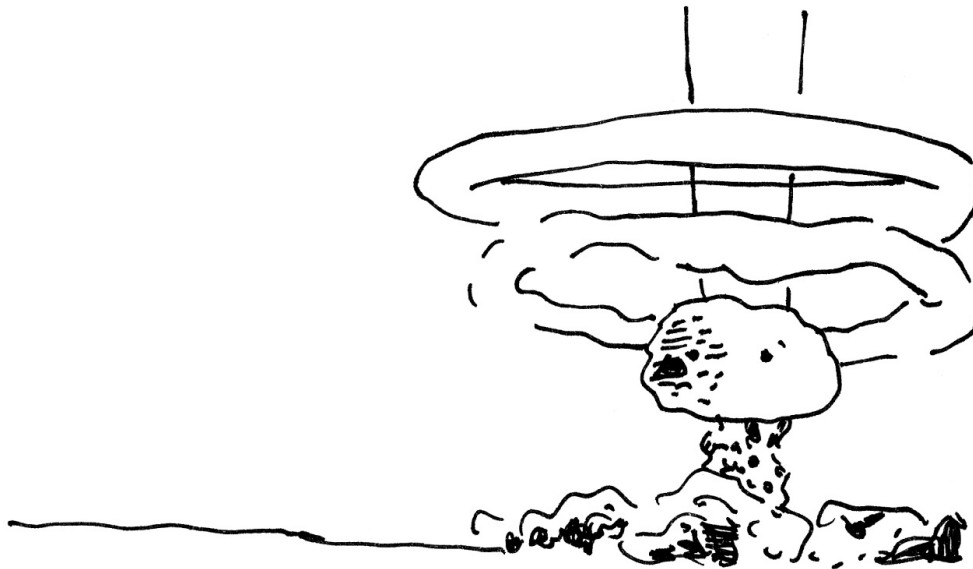
B: The reason why insects are limited in size is not entirely understood. The most widely accepted explanation is that they breathe in a very different way to us. Oxygen is transferred around an insect's body through tubes known as trachea. The idea is that this passive method is too inefficient for very large bodies, and this ultimately restricts their size. This theory is supported by the observation that insects were much larger in the past when atmospheric oxygen levels were higher; 300 million years ago the oxygen content of the atmosphere was 35 per cent, rather than 21 per cent today, and there were giant insects. The largest dragonfly fossils have wingspans of around three-quarters of a metre, as opposed to the hand-sized White Witch Moth, which has the largest wingspan today. It's small, relatively speaking, but you still wouldn't want one on your face.

Some researchers also note that insect size declined during the late Jurassic period when birds began to dominate the skies. The decrease in size may have been an evolutionary response to this challenging new predator.

R: *If two nuclear tests did coincide, one at each Pole, could we be sent speeding towards the Sun?*

B: No.

R: I suppose the main threat from nuclear weapons remains the destruction they are designed to wreak and their terrifying long-term ramifications. There'll barely be time for the ants to mutate before we are destroyed by the blast or its side-effects, so that's a relief.

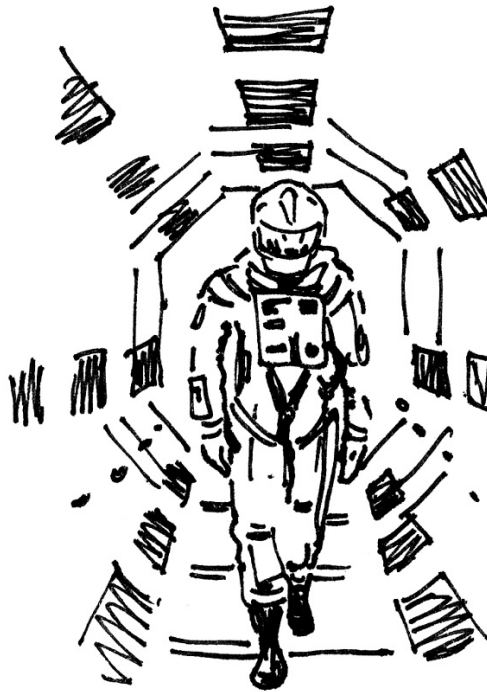


B: Yes. I'm always amazed by the speed at which mutations, presumably caused by the exposure of DNA to the ionising radiation from the bomb, result in a change in size of the animal. This represents a gross misunderstanding of the rate at which evolutionary change occurs. But I suppose a film in which the ants become gradually larger over many thousands of years would be less compelling.

By the way, my cameraman on my documentary series once coined a phrase for the artistic licence that is sometimes deemed necessary⁵ at the interface

between Science and Art. SHART.

R: Science fiction has spent much of its life underrated and belittled. You'll rarely find it winning literary prizes or Academy Awards beyond the categories of special effects. Too much imagination or depth is scorned if you want to be taken seriously. This has changed in the last few decades, though, with the literary works of Doris Lessing and Margaret Atwood and the films of Christopher Nolan and Denis Villeneuve, prefigured by Stanley Kubrick and Andrei Tarkovsky.



Stanley Kubrick was renowned for his scrupulous desire to retain as much accuracy as possible when making *2001: A Space Odyssey*. There is the old joke that NASA asked him to direct a film that would hoax the public into believing humans had landed on the Moon, but he insisted he would only take the job if he could film on location.⁶ Kubrick's meticulous desire for accuracy led to his umbrage and dissatisfaction when our view of the Earth from lunar orbit revealed its colours to be far brighter and more vivid than he had imagined in *2001*.



On the set of Stanley Kubrick's *2001: A Space Odyssey* (1968).

The science of Science Fiction has become increasingly real this century. Astronaut Chris Hadfield's return to Earth coincided with excitement over the Sandra Bullock film, *Gravity*.



His opinion of it was frequently sought. One of his main criticisms of its accuracy was the underwear.

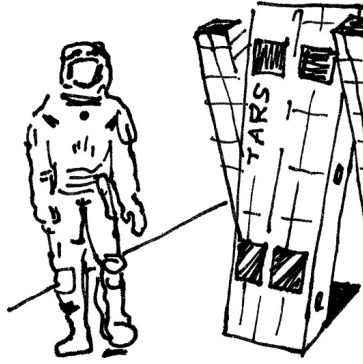
The underwear of space is less glamorous than the underwear Hollywood requires Sandra Bullock to don, gravity or no gravity.

While in LA on a US tour of *Monkey Cage*, the eminent cosmologist and author Sean M. Carroll joined us on the panel. Being a cosmologist in LA, he has acted as science advisor on numerous movies. The most surprising film that required a science advisor was *Thor*. We asked what scientific veracity was required in a film about a mythical Norse god with a big hammer. Sean looked as if the answer should have been staring us right in the face, ‘obviously they wanted the wormholes that the god of Asgard travelled through to be as authentic as possible’.

Sean told us that his main contribution was that the creators didn’t really like the term wormhole as it sounded ‘too 90s’, so he gave them ‘Einstein-Rosen bridge’ instead, as well as suggesting Natalie Portman’s character should be a particle physicist. It is uplifting to think that one day a Nobel Prize winner may be thanking a mythical Norse God Thor for inspiring their pioneering work into quantum gravity.

‘Every movie needs to have its own world and its own standards. If there is suddenly a talking tree in Gravity that would seem odd, but it works perfectly well in Guardians of the Galaxy. The question is, are you thrown out of the world? Does the drama work?’

Sean M. Carroll, Series 12, Episode 2 (13 July 2015)



In the future, increasingly scientifically accurate Hollywood that we all desire, Thor will become a man in an iron hat dragging his hammer along the sidewalk having had gravity explained to him, coupled with the fact that carrying a hammer is likely to make you less, not more, aerodynamic.

Interstellar has been one of the most celebrated science-fiction movies to use science as its inspiration. The film was inspired by discussions between theoretical physicist Kip Thorne and film producer Lynda Obst while they worked together on the screen adaptation of Carl Sagan's *Contact*. Thorne had suggested that *Contact*'s lead character, Ellie Arroway, travelled through space via a wormhole, but realised that if you travelled faster than the speed of light you could go backwards in time, violating causality, which we believe to be fundamental, and he wrote a paper on it. And as should happen with all good physics papers, it inspired a film.



B: My most successful scientific paper to date, in terms of citations, is one I wrote in 2002 with, coincidentally, two future *Monkey Cage* guests, Professor Jeff Forshaw and Professor Jon Butterworth. The paper is entitled 'WW Scattering at the LHC' (Phys.Rev. D65:096014, 2002), and at the time of writing has 277 citations. Perhaps that could be made into a film? It

appears, by the way, pinned to the wall of Cillian Murphy's bunk in the film *Sunshine*.

R: In one of the earliest *Monkey Cage* episodes, we were joined by one of the world's most imaginative writers and finest magician autodidacts, Alan Moore, to discuss science fiction and science fact. During the programme, Alan had it confirmed that some of his most fanciful ideas were more tethered to ideas in science reality than his readers might have imagined. In *The Ballad of Halo Jones*, he wrote about a planet so massive that time was bent as a function of gravity. The theoretical physicist and mathematician Brian Greene nodded, 'that's absolutely correct. And if you wrote that before 1915, you are a genius.' Sadly, Alan had not written it before 1915... yet.

Do not expect the science to be accurate in fiction, but don't dismiss it out of hand, either. Great science fiction, even plain old good science fiction, is often an introduction to ideas that you can explore. It is a series of what-ifs, and the scientific process can also begin this way.



B: My paper deals with what physics at the LHC might have been like if a light Higgs boson did not exist. The Higgs was discovered, of course, which makes it a sort of 'what-if, alternate future' film plot. Cillian Murphy could reprise his impression of me in *Sunshine*, and perhaps Danny Boyle would direct again, and...

R: When Alan Moore reads his copy of *New Scientist* every Thursday, he will come across ideas at the cutting edge of understanding that set off a chain of imaginings. When he first read about String Theory, he wrote an eight-page story about 'a guy with a superstring violin that can alter reality'.

As he told us, he doesn't believe it to be a true proposition, but it is a poetic conceit based on ideas of science, and for his readers it might be the first time they come across the idea of String Theory. And so, to the library...



B: The part of the abstract that I think could go directly into the film script, is:

A detailed study is presented of elastic WW scattering in the scenario that there are no new particles discovered prior to the commissioning of the LHC. We work with the framework of the Electroweak Chiral Lagrangian and two different unitarisation protocols are investigated. Signals and backgrounds are simulated to the final-state particle level.

This is the good bit now – the bit that gets all the citations.

A new technique for identifying the hadronically decaying W is developed, which is more generally applicable to massive particles which decay to jets where the separation of the jets is small.

Obviously, we could only explore one unitarisation protocol in the film, if we wanted to edit the story down a bit to include more giant ants or something. Or we could only simulate the final state at the parton level.



R: Good fiction requires a consistent world, a world where the laws and rules are not conveniently changed to make a plot point easier. This is what annoyed people about *The Matrix* universe in the follow-up films. Having seemed so methodical in the first film, the sequels seem far less concerned with consistency. ‘Hey Neo, you can fly!’ ‘Sure, didn’t I mention that before?’

In this way, good science fiction mirrors effective science. A new scientific theory would not normally be expected to contradict other well-established theories, particularly in other areas of science. If it does, it may still be correct, but then the whole back story must be rewritten. We expect science as a whole to deliver a consistent, contradiction-free picture of the Universe.

B: The final speech could be delivered by Sandra Bullock, spokesperson of the ATLAS experiment at CERN.



‘We have performed a study of the WW \rightarrow WW scattering cross-section in the scenario that there is no new physics below the TeV scale using the formalism of the Electroweak Chiral Lagrangian extended by the imposition of unitarity constraints.’

Cinema Gold. Robin, do you have J.J. Abrams’s number?

¹ Remarks on the 20th Anniversary of the Apollo 11 Moon Landing; 20 July 1989, www.presidency.ucsb.edu/ws/?pid=17321

² The Economic Impact of NASA R&D Spending, Chase Econometric Associates Inc.; April 1976, <https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19760017002.pdf>

³ Kevin Fong is medical doctor and expert on medical needs for differing environments of space exploration.

⁴ *Capricorn One* was a 1977 film about a Mars landing hoax.

⁵ Deemed necessary by cappuccino-sipping millennial media executives in three-quarter-length jeans and characterful shoes who live in Shoreditch and commission documentaries based on an ‘idea’ that popped into their minds during a thought shower.

⁶ Since his death – death always being an advantage when you want to attach someone to nonsense they would have rejected when alive – Kubrick has been drawn into Moon hoax ideas by conspiracy theorists. His daughter, Vivian, has energetically rebutted these claims. ‘Surely an artist such as my father, whose profound degree of artistic integrity is self-evident, whose political/social consciousness is manifestly present in nearly every film he made... don’t you think he’d be the last person EVER to assist the US government in such a terrible betrayal of its people?’



No.5

Evidence & Why Ghosts Don't Exist



HOMEOPATHY

E = Duck's liver –
lose the mass and cure the cold
The nostalgia of arnica
You can't cross out the small –
size matters



‘The ancients had a secret’ is a popular cry to reject the contemporary while selling books and ointments apparently inspired by ancient Aztec elders – though the human hearts sold by high-street herbalists are apparently made of tofu. There are reasons not to wholeheartedly trust the big pharmaceutical industries, but distrust of one group does not instantaneously mean that anything in opposition is trustworthy, good and pure.

Pseudoscience and alternative medicine frequently utilise ingenuous charlatanism. The explanations for their efficacy rarely survive serious scrutiny. If they did, the pseudoscience would become science and the alternative medicine would become medicine. A reason for the success of non-evidence-based medicine, as it should be called, is that we are often less comfortable with evidence-based scrutiny than with pleasing anecdote that lends credence to our preconceived views on what we wish something to be. This is a natural human response; our health is the most valuable thing that we possess as individuals, and it is very hard to be objective about it. After all, ‘natural’, ‘herbal’ or ‘holistic’ sound better than ‘synthetic’ or ‘drug’ or ‘positron-emission tomography’. We are therefore predisposed to applaud the cosy inventiveness of the alternative, and if

there is an occasional sprinkling of equations or a veneer of sciencey language, then that only adds to the veracity of the snake oil pitch.

Homeopathy, in particular, has avoided serious scrutiny until quite recently. Talk to many users and it seems they believe it is something herbal, a pill 'with some natural stuff in it'. Few know the 'theory' behind it; that the very advantage of these pills is that, unlike many of the pills at the chemist, the boast of these is there is nothing in them at all save for a memory, a nostalgia of arnica. What could be more natural and free of nasty chemicals than nothing? If a human being was free of chemicals, by the way, it would be a radiation pattern, and even radiation has a bad name these days. 'Chemicals are bad for you!', but we are chemical processes. 'Natural is good!', death is natural.



On 30 January 2010, sceptic groups led by the Merseyside Skeptics Society organised a mass homeopathic overdose outside high-street retail chemists as part of the 10:23 campaign.^{[1](#)} The idea was to demonstrate that these pills do nothing whatsoever; the greatest risk is their sugar content.

Oscilloccoccinum is one of the poster children for the sceptic who cannot see how dilution upon dilution will lead to cure. Homeopathic remedies start

from the idea that ‘Like Cures Like’. If you have a skin condition that causes itchy red welts, you should consume a shrub or herb or offal that causes big, itchy red welts. The trick is to mix the shrub, herb or offal with water first. The practitioner dilutes the active ingredient in water, then dilutes the dilution, then dilutes the dilute dilution and keeps going methodically until they have a solution that has no trace whatsoever of the original shrub, herb or offal – presumably because any measurable trace would lead to the user breaking out in big, itchy red welts. Only an untraceable yet active memory of the pathogen is left behind.



Oscillococcinum is a cure for flu made using a duck’s liver. The suggested dilution for maximum effectiveness requires more water molecules than there are atoms in the Universe per liver.

In 2015, we recorded an episode entitled ‘When Quantum Goes Woo’ (Series 11, Episode 4, 9 February 15). Quantum mechanics is so counter-instinctual to our hunting-mammoth, berry-collecting, football-chanting, Sudoku-on-commuter-trains brains that it can be used as a sales pitch for all manner of mystical poop.

Researching the most flamboyant uses of physics to mis-sell an idea, we came across a relativistic sales pitch for homeopathy.

Einstein was being used to justify Dr Hahnemann’s Nostalgia Water, and we were not sure if he would have liked it. We don’t know this for sure, though, because when we tried to contact Einstein’s spirit using the BBC

ouija board we got put through to the wrong after-life department and got a load of fashion tips from Coco Chanel. The hat looked lovely on Brian, though, really lovely wren feathers...

The Einsteinian explanation for homeopathy was simple. It was based around Einstein's most famous equation and revolved around the m in $E = mc^2$. The mass of the Universe is really very small, because if you take out all the empty spaces from the atoms, there isn't much left. This last part is true and quite remarkable. For a world that seems so solid, it is surprising how much of reality is empty space with strong forces, to which we are mostly oblivious, working away deep within. Gravity is the weakest force in the Universe and that can still hurt quite a lot if you bend space clumsily while trying to walk in flip flops.



The presumption that the homeopathic lecturer (diluted content) made was that as m is so small, in many ways you can pretty much cross it out, thus leaving $E = c^2$. Could this be true? Einstein was pretty clever; if he could have taken a shortcut and said, 'you know what, $E = c^2$, that'll do. Pub?', surely he would have done.

What did Brian Cox think? Could we cross out the m ?

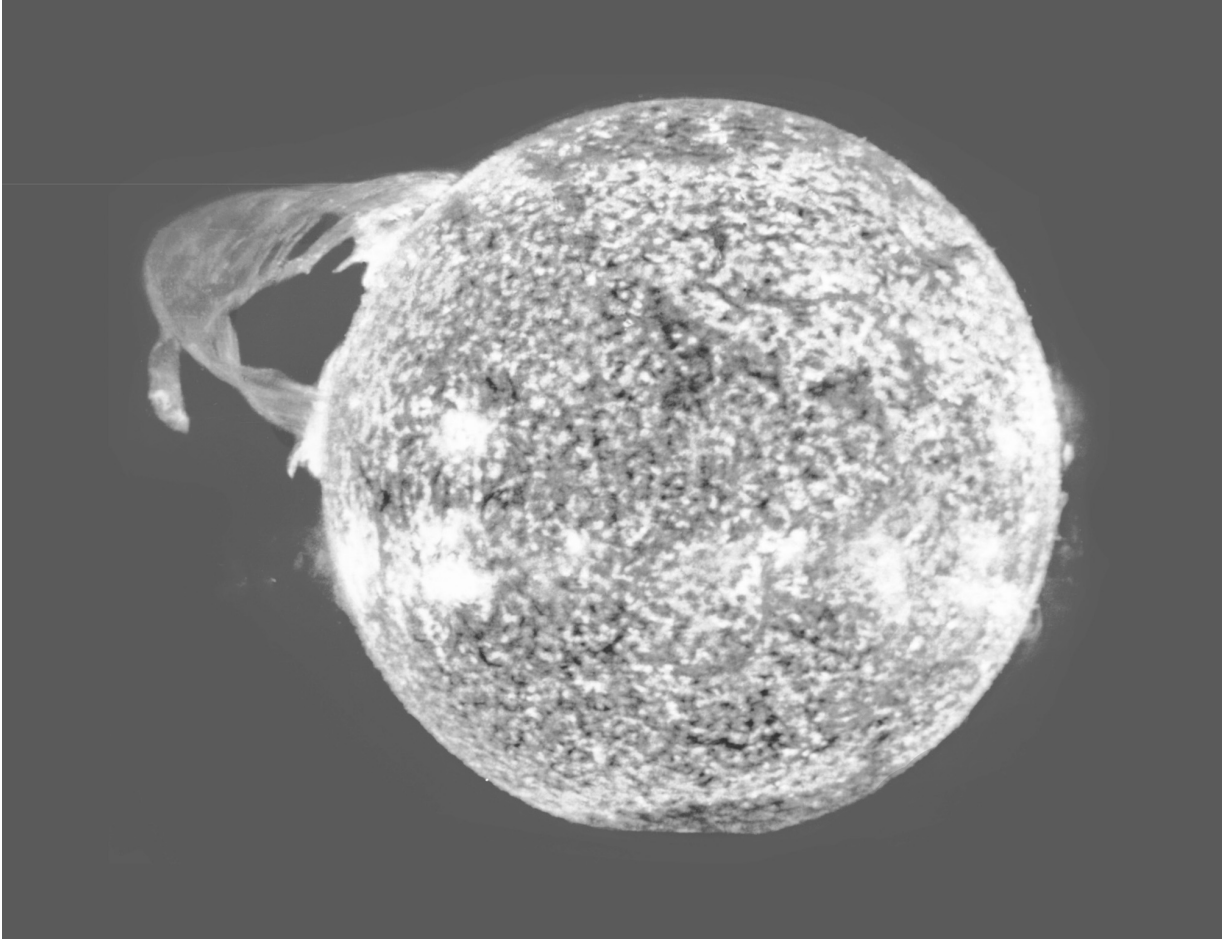
BRIAN: The equation $E = mc^2$ is the most well-known equation in physics, but what does it mean and where does it come from? E stands for energy, which is an interesting quantity to a physicist because it is conserved. This means that if you calculate the total energy of a system of particles or objects before and after something happens to them, the energy will be precisely the same before and after. This is what makes the concept of energy useful. $E = mc^2$ follows from a more general equation for the energy of a particle in Einstein's theory:

$$E = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} mc^2 ,$$

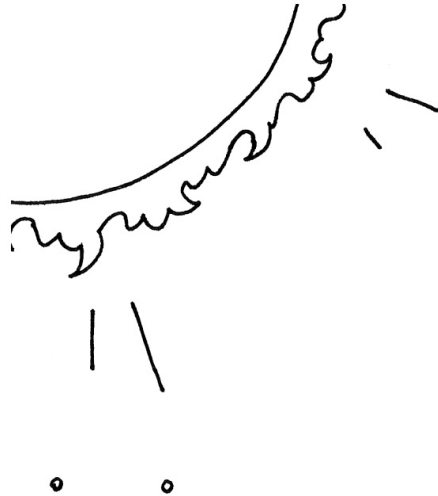
where v is the speed of the particle, m is the rest mass of the particle (see [below](#)) and c is the speed of light. For a system of particles, we would calculate the energy of each particle in turn and then add up all the energies to get the total energy of the system. For particles moving with speeds small enough to be compared to the speed of light, this equation reduces to:

$$E = mc^2 + \frac{1}{2} mv^2 + \dots$$





This photograph of the Sun, taken on 19 December 1973, during the third and final manned Skylab mission, shows one of the most spectacular solar flares ever recorded, spanning more than 588,000 kilometres (365,000 miles) across the solar surface.



If you remember a bit of school physics, you will recognise the second term $\frac{1}{2}mv^2$ as the kinetic energy – the energy a particle possesses due to its motion. Notice that, even if the particle is not moving, it still has energy $E = mc^2$, where m is called the ‘rest mass’ of the particle. Because only the total energy of a system must remain constant, a particle or system of particles can lose mass, as long as this is compensated for by a corresponding increase in kinetic energy. A good example is the nuclear fusion of hydrogen into helium inside the Sun, in which four protons turn into a single helium nucleus plus two electrons and two particles called electron neutrinos. The sum of the rest masses of the four protons exceeds the sum of the rest masses of the five particles remaining after the nuclear fusion reaction, and the missing mass is accounted for in the kinetic energy of the remaining particles. This is the source of the Sun’s heat.

Energy is a useful accounting device because it is conserved, which is a good definition you can recite next time someone starts talking to you about their atrophied ley lines caused by negative energy from Stanley Kubrick’s Moon Show.

Where did the equation $E = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} mc^2$ come from?



Einstein discovered it in 1905 as part of his Special Theory of Relativity. He was forced to reformulate physics in order to satisfy two ‘postulates’, which are statements about the fundamental structure of our universe. The first postulate states that it is impossible to conduct any experiment to determine whether we are moving at a constant speed. Physicists refer to our point of view as a frame of reference, and one that is moving with a constant speed is known as an inertial frame of reference. To be more precise and concise, we could state Einstein’s first postulate as ‘Identical experiments in different inertial frames give identical results’. This postulate cannot be derived; it comes from careful observation of the way things behave in nature. Einstein’s second postulate states that the speed of light through empty space is the same in all inertial frames of reference. He was inspired to make this statement by James Clerk Maxwell’s theory of electricity and magnetism, itself based on the experimental work of Michael Faraday and others. The second postulate is therefore also motivated by experimental results, and cannot be derived. It is a consequence of these two postulates that $E = mc^2$, and the derivation is not so difficult. It is taught in the first term of a university physics degree course, and uses only a little A-level mathematics.



Let us now consider why Robin's homeopathic lecturer was wrong to suggest that because the mass of an object can be very small or even zero, this implies that $E = mc^2$. Clearly this is nonsense, because setting m to zero would appear to set E to zero in the above equations.

There is something significantly more interesting that we can salvage from the stupidity, however, because an object with zero mass does not have to

have zero energy. The subtlety comes from the term $\frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$

What happens if the particle is travelling at the speed of light? This term becomes $1/0$, which is infinite. For a massless particle travelling at the speed of light, therefore, our equation for the energy becomes infinity multiplied by zero, which is mathematically undefined. The equation as it stands is useless, and we are not entitled to conclude that the energy of a massless particle is zero for the specific case of a particle with speed c .



There is another similar equation in relativity for the momentum of a particle:

$$p = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} mv$$

If we divide our equation for the energy by the equation for the momentum, we get

$$\frac{E}{p} = \frac{c^2}{v}$$

which for the special case of a particle moving at the speed of light, $v = c$, becomes

$$E = pc$$

So, the energy and momentum of a particle can be well-defined and non-zero for a particle of zero mass, but *only* if the particle travels at the speed of light. In this way, Einstein's theory allows for the existence of massless particles. Photons, particles of light, are massless, and this is ultimately why light travels at the speed of light!

Perhaps this is what Robin's homeopath was trying to say, but it is unlikely.

ROBIN: So the moral of this story is as follows: if you decide to cross out physical constants or quantities because they seem pretty dinky, you may find yourself crossing out the entirety of physics. Sometimes physics needs very, very small numbers to make theories effective and the Universe viable. The reputation of a scientist is not based on the enormity of the number remembered in their name. Avogadro's number ($6.022140858 \times 10^{23}$) is many orders of magnitude larger than Planck's Constant in SI units ($6.626070040(81) \times 10^{-34}$ Js), but this does not mean that Avogadro was a better scientist than Planck, or that we can ignore quantum mechanics. You might consider that π goes on for way too long after the decimal point, but don't decide that you can round it down to three, you'll find it much harder to build things that don't fall down.



Whether you cross out the m or not, if you have flu, we recommend actual chicken soup and a blanket rather than the memory of a duck's liver.

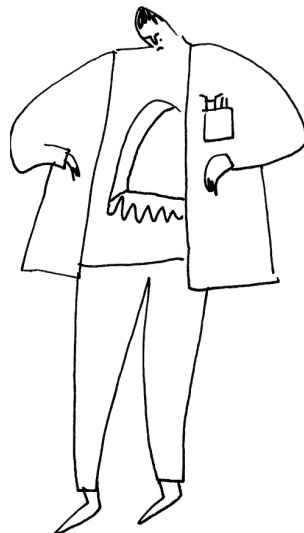
WHY GHOSTS DON'T EXIST (OR DO THEY...?)

‘I think ghosts are perpetual motion machines. They violate the laws of thermodynamics as far as I can see.’

Brian Cox, Series 4, Episode 6 (4 July 2011)

One of the most frequently asked questions when thinking about becoming a scientist is ‘will I still be allowed to believe in ghosts?’

They say the atheist can feel a god-shaped hole.
The vegetarian may suffer a bacon-shaped hole.
But does the scientist ever feel a ghost-shaped hole, and if so, what sort of shape is that?



BRIAN: We aim to list every paranormal phenomenon that has occurred through all of human history that cannot be explained by science.
Goodnight.

Everyone has seen a ghost, haven't they? It just depends how long your frontal lobes will let you continue to believe that. Brought up on myths, legends and fireside ghost stories, it is hard not to feel a little hint of a ghostly hand on your shoulder, or to see an uninvited face in the mirror on a dark and stormy night. Even a hard-nosed, granite-eyed, flint-eared sceptic may succumb to brief senses of a haunting if left in a sixteenth-century barn where one candle flickers and manufactures shadows that to an untrained eye may hint at the uncanny.

Take a shortcut through a large, open cemetery after a night in the pub and more often than not you'll find that when you've walked halfway across it your peripheral vision alerts you to the savage ghost of an angry nun. The frontal lobes are jettisoned and the amygdala says, 'you know, I'm sure it's nothing, but RUN!'

The more successful sceptic will not be startled by a ghost, they'll decide that they are being startled by a very real, angry nun seeking vengeance for some anti-papal crime and her or his amygdala will also say, 'it's probably nothing, but RUN!'



As the urban foxes scatter and you reach the furthest wall, the frontal lobes take hold and the angry nun returns to being what she always was, one of those annoyingly nun-shaped gravestones that masons are so keen on.

ROBIN: I was fortunate enough to work on a radio show with the great actor Sarah Miles, star of *Ryan's Daughter*. She approached me eagerly and said,

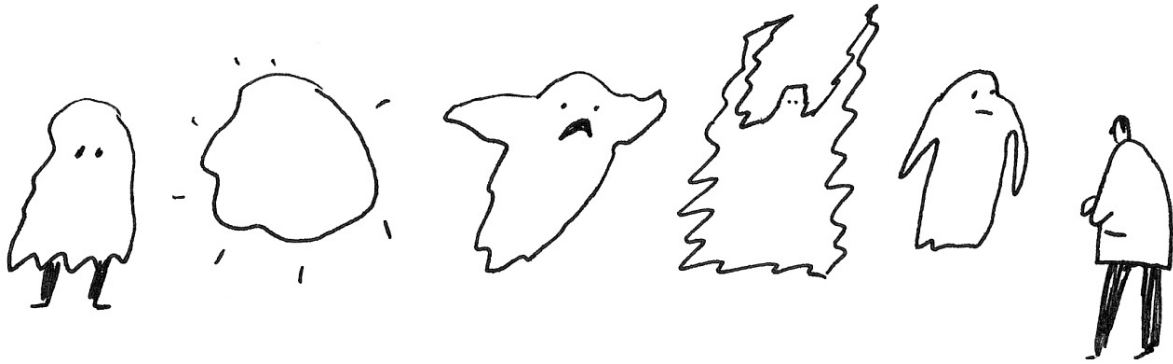
'You know Richard Dawkins, don't you?'

I said I knew him a little bit.

'Good, maybe you could help me. He doesn't believe, does he? Well, I can make him believe. There is a house near me that is haunted by many ghosts. I want to get him there, chain him to a bed and leave him there alone overnight, then he'll believe. Could you help me get in contact with him?' Always wanting to help, I gave her his email details. I'm not sure if he's been chained yet.

If we wish to discuss the likelihood of ghosts being allowable under the laws of this universe, first we must define a ghost. I presume it is an energy left behind by someone or something that has died and that can in some way interact with our world on a level that can be perceived by some, if not all, of our senses.

B: If you're asking me to define a ghost, I can't, because I can't define something with any rigour that doesn't exist. How about 'an embittered caretaker in a costume scaring dogs and hippies with the hope of financial gain, who would have gotten away with it too if it wasn't for you meddling physicists'?



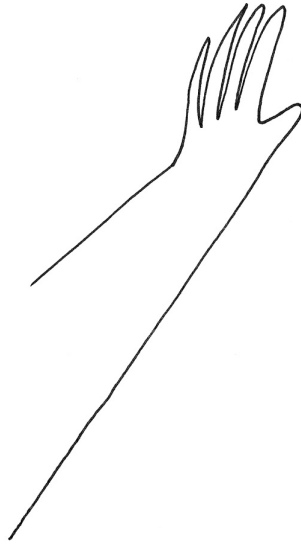
R: The Usborne book of *Haunted Houses, Ghosts and Spectres* describes ghosts as most frequently being ‘the spirit of someone who has died’. It considers ghosts to be different to phantoms as ‘they look so solid’. Some ghosts are surrounded by haloes or glowing light, others are colourless or transparent.

Brian, the question is, why do you physicists consider the idea of an apparition seemingly in the shape of a deceased human, and possibly holding its own head in its hand, so unlikely?

B: If there is a ghost/soul that persists after death, it must carry information about the person in question – it knows it had the head chopped off its body, in your example, and knows what that head and body looked like when they were alive. Furthermore, presumably, the soul *is* the person in some sense when they are alive – the ghost in the machine, the operator of the particles that make up human bodies. If we accept those two broad points, then some things follow.

The ghost/soul must be made of something, since it carries information. We are at liberty to postulate that the ‘something’ is a substance unknown to science, and it is certainly possible that there might be ‘stuff’ in the Universe that we haven’t discovered yet. But there are constraints on how this new stuff must behave, because we do know some things about it. We know that it must interact with normal matter. Why? Because the ghost ‘knows’ what the matter of the body looked like – it resembles the living person. The soul therefore carries information about something material and physical, and must therefore have interacted with it. Furthermore, if the soul really is the essence of a person – you, for example – it must be constantly interacting with the matter that makes up your body. It is telling your hands

to hold this book, changing the focus of your eyes as you read and controlling your every movement.



If we want to postulate the existence of a ghost/soul, therefore, we must specify how the (unknown to science) substance out of which it is made interacts with normal matter. This is extremely difficult to do, because we know very well how matter interacts. Particle physics is the study of matter and its interactions, and it is one of the most high-precision areas of science. Quantum Electrodynamics (QED), for example, is our theory of light and matter; it describes how matter interacts via the electromagnetic force. This is the force that is entirely responsible for your experience of the world. You see because photons – particles of light and carriers of the electromagnetic force – enter your eyes after being emitted by or bouncing off external objects and interact with molecules in your retina. You touch because the electrons in your fingertips interact with the electrons in an object via the exchange of photons, and so on. Since you can ‘see’ a ghost, the ghost stuff must interact with photons and it would therefore be necessary to incorporate this stuff into the theory.



How accurate is QED? There is a calculation of the way electrons behave in a magnetic field which is tested experimentally in so-called g-2 experiments. These experiments are sensitive to *everything* that photons can interact with, and much more besides. The current agreement between calculation and experiment is at the level of 1 part in a hundred million. Interestingly, the g-2 measurement of the electron's heavier cousin, the muon (see [here](#)), currently shows a discrepancy between theory and experiment that may be the signal of new particles or forces. There is a very exciting experiment called Muon g-2 at Fermilab, near Chicago, which is currently probing this anomaly more deeply.

The bottom line is that if there is some other way in which matter can interact, it is extremely subtle and extremely weak at the sort of energies at which human bodies function. Such a force may become important very close to the Big Bang, when energies are extremely high, or may show up in high-precision g-2 experiments, but at 'room temperature' the influence of such a new force or particle on the protons, neutrons and electrons that make up your body is constrained to be almost vanishingly small by many decades of data.



You are free, of course, to challenge this assertion, but only by presenting a theory for the ghost/soul stuff that leads to predictions that have not been ruled out by experiment. The challenge to a believer in ghosts, therefore, is to come up with an extension to the Standard Model of particle physics which is consistent with all experimental results on the search for a fifth

force of nature, and yet is strong enough to provide a plausible mechanism for the ghost/soul to influence the behaviour of your body, which nobody disputes is made of protons, neutrons and electrons.

‘Just because you are a scientist or a budding scientist doesn’t mean you understand everything you encounter. Many things you don’t understand and what separates the gullible from the inquisitive is that the inquisitive person explores precisely what they don’t understand to try to come to understand it. I’ve yet to really find a phenomenon that has defied my complete knowledge of physics and math and astrophysics.’

Neil deGrasse Tyson, Christmas Special (27 December 2016)

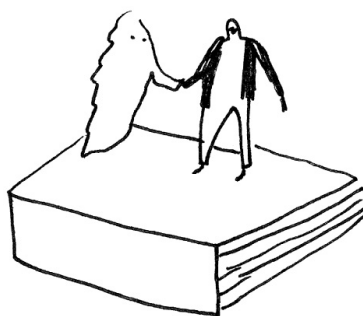


R: If the ghost of Lord Kelvin came to you and told you that he reckoned the Second Law of Thermodynamics needn’t get in the way of him haunting you, how would you feel?

B: I’d ask him to co-author a paper with me on his findings and collect my Nobel Prize.

Actually, this raises a point that is often missed by the ‘sceptic’ who asserts that scientists are all members of some sort of secret society whose *soul* purpose (see what I did there?) is to defend the status quo. The greatest rewards in science, both reputational and financial, go to those who discover new phenomena and overturn the current consensus. The reason why this happens very rarely is because it is very difficult to do. In a sense, one of the great tragedies, but also challenges, of being a scientist in the twenty-first century is that most of the easy stuff has been discovered!

In summary, I would be absolutely delighted to publish Cox and Kelvin, ‘Evidence for the existence of the ghost of Kelvin’, *Nature*, 2018. But I don’t think it will happen.



If people can move things around with thought, or a glass of water flies up into the air without any action, that requires us to rewrite the laws of nature. This is Nobel Prize-winning stuff.

Neil deGrasse Tyson: Yes, I’d be all up in that situation.



R: If I give Sarah Miles your home number, would you agree to go and be chained to a bed in her haunted house?

B: I think we should record an all-night Monkey Cage there. We could have a ghost on the panel.

R: Do you think the Large Hadron Collider's greatest contribution to human understanding will eventually be seen as its achievement in dispelling ghosts as a notion rather than aiding our understanding of why the Universe has mass?

B: No. In any case, I think the Muon g-2 experiment is probably more sensitive to new physics.

R: Hang on, what if ghosts are apparitions from one of the many other universes, is that allowable?



B: I'm assuming you mean extra dimensions? The answer would be no, because if extra dimensions do exist they are not visible to us at room temperature. According to your ghost theory, we can see ghosts, and this means that they interact with photons. Photons certainly do not travel between the extra dimensions, so this idea falls at the first hurdle. As a matter of interest, we do look for extra dimensions by looking for energy vanishing off into them in particle collisions at the LHC. This energy could conceivably be carried away by gravitons – the carriers of the gravitational force in quantum theories of gravity. We have seen no signal to date.

R: Okay, what about werewolves?



In the summer of 2013, the Muon g-2 team successfully transported a 50-foot-wide electromagnet from Long Island to Chicago in one piece.

How to write a science slogan

On 22 April 2017, people around the world marched for science. It was a march to celebrate intellectual progress and highlight the need for governments to safeguard and encourage scientific research. It was a beautiful sea of spectacles and lab coats. The march was dominated by young researchers, PhD students and lots of people who just really enjoyed looking through telescopes and hungered for evidence-based policy in government. The oldest person there was somewhere between 2000 and 4 billion years old – there is some debate about this, for it was the Doctor. In reality, it was the then-current actor playing the Doctor, Peter Capaldi, who is fascinated by science both as his fictional character and in reality as a human actor. Some marches have a uniformity when it comes to placards, but the night before there had clearly been much beavering with cardboard and marker pens. There were images of Einstein declaring, ‘Science Cuts Makes Me Relatively Angry’, ‘There is no Planet B’, ‘Science, it’s like Magic but Real’, ‘ $1 + 1 = 2$ ’ (and don’t forget, it took Bertrand Russell and A.N. Whitehead ten years and a few hundred pages in *Principia Mathematica* to work this out so that we didn’t have to). Not forgetting ‘Censorship of Scientists is why Krypton Exploded’.

The biggest problem when marching for science is coming up with chants; they have to be scientifically accurate, which can get in the way of the rhyme scheme. These were chants that required footnotes and addenda. Someone at the front of the march would strike upon a chant, but as it rose to the sky, a sudden hush would be enforced – ‘hang on a minute, the subject of that chant is hotly under debate according to the latest issue of *Epigenetics Monthly*’. Then everyone would have to hurriedly return to the drawing board of their minds seeking chants that would pass peer review.

For those hotly anticipating another March for Science, or any other science gathering that requires chants or slogans, opposite

are some starter chants for you to work with.

When the chants were at their most delighted and exuberant, those at the front of the march would set up an experiment to see if a Mexican particle could also act as a wave, and vice versa. Up went the shout of ‘Give us a particle!’, and the throng would shout ‘particle!’ while creating the best sense of particle via fist and gesticulation. ‘Give us a wave!’ came next, and from the front, up would go a wave, and we would see if such a cause would have the effect of going all the way to the back of this crowd of 12,000. It never quite made it all the way to the back. That’s the trouble with freethinkers, they have a problem being overly communal, especially when it comes to choreography. Now we have given you a few starter chants for your next March for Science, why not come up with your own?

What do we want? _____

When do we want it?

—

Good luck. No, hang on, luck isn’t very scientific. Hmmm. We hope the probabilities of the outcomes from your next march² are predominantly positive.

Chant No. 1

Inspired by the failure of the first few slogans to pass muster:

**What do we want?
Evidence-based policy!
When do we want it?
After peer review!**

Chant No. 2

One of the core reasons for the march was highlighting the necessity for governments to deal with climate change effectively. So,

**What do we want?
Climate change!
When do we want it?
Over geological timescales!**

Chant No. 3

Quantum indeterminacy must always be dealt with on a march when living in a probabilistic Universe:

**What do we want?
Cats in a superposition!
When do we want them?
Until observed!**

AN ARGUMENT

Perception



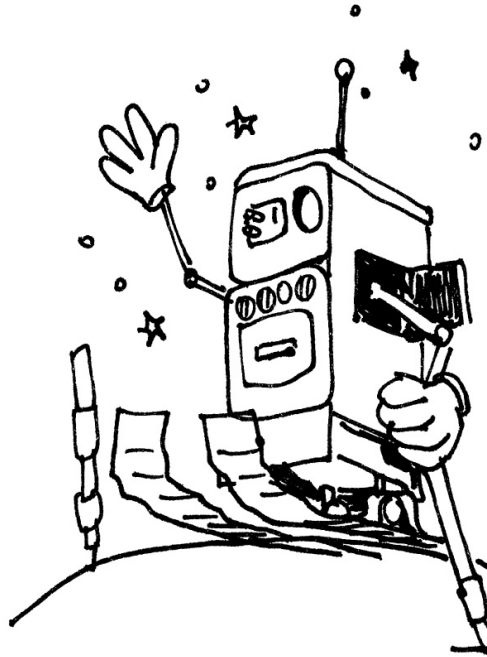
Arguments are rare during the making of *The Infinite Monkey Cage*, but when they do occur, they can be furious.

More often than not, they will revolve around some logic. Brian is very logical. He is also addicted to equations. During the recordings, where Brian is unable to use a whiteboard, he has a small patch attached to his thigh which seeps small amounts of Maxwell's Equations into his bloodstream. In Brian's mind, if there's not an equation for it, it doesn't exist. At times, it is like working with a Vulcan; 'what is this human emotion called love?'

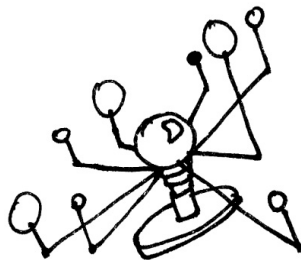
The first stand-up row we had concerned perception. Later on that evening we would sit down and discuss the mental construction of reality with Beau Lotto, Claudia Hammond and the magician and comic-book shaman, Alan Moore, but first we had to scream at each other.

People are not used to seeing Brian perturbed; even when talking about the extinction of all life on Earth and the eventual heat death of the Universe, a beatific grin is spread across his face. His eyebrows snapped into the angle of fury when I repeated a quotation that I believed had some relevance to our discussion: 'you cannot observe nature from outside of nature'.

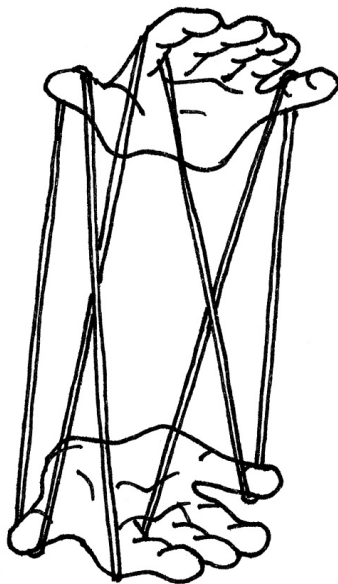
Welcome to the *Infinite Monkey Cage* re-enactment society, for the first time in five years, we will attempt to come to a conclusion once and for all.



ROBIN: From my perspective (non-equation-understanding arts type with a better knowledge of *Beowulf* than Heisenberg), the human inability to understand nature from outside of nature is quite simple. We have evolved with the rest of life on Earth. Our brain functions, through mutation, heredity and natural selection, are adapted to enhance survival and we consider ourselves to have faculties of perception and an extraneous curiosity that surpasses all other living things on Earth. We are able to build vehicles that will allow us to explore space, and particle accelerators that will allow us to explore the subatomic, but this does not mean that our brain is not limited by evolution. When we investigate nature we may still be limited by the brains that have developed through the same processes as the rest of nature. We are not above and beyond nature and may never even be aware of the limitations imposed on us, because we will never be able to raise ourselves above our faculties.



BRIAN: This may be true, or it may not. It is speculation, and as such the information content of the assertion is vanishingly small. What we can say is that our brains have allowed us to construct models of the way the external Universe behaves which have been extremely successful. Einstein's General Theory of Relativity, for example, has allowed us to interpret observations of the light from distant galaxies such that we can say with some confidence that it is 13.8 billion years since the Big Bang. Our theories also allow us to predict the existence of things that have been subsequently discovered. The Higgs boson is an excellent example. The Standard Model of particle physics represents our current understanding of atomic and subatomic physics, and three of the four fundamental forces of nature. The existence of a new particle – a real, material thing external to and completely divorced from our everyday human experience – was confirmed at the Large Hadron Collider half a century after its prediction. I do not claim that this necessarily implies we will have access to a 'theory of everything' – a complete understanding of the Universe – at some point in the future. We may or may not be intellectually capable of this, even if such a thing exists. All we can say is that our intellectual capabilities have served us very well so far, when harnessed through the humble practice of science.

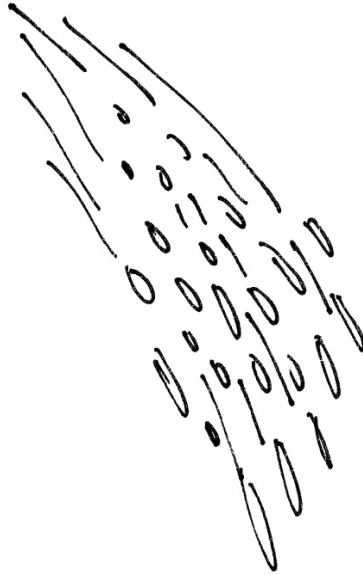


R: This argument is very different to the stand-up row we had before the show. You never got to 'this may be true, or it may not', you just called me an idiot and said it was rubbish. I think this might have come from pie

anger, the sensation of fury you experience when it has been over three hours since you last had gravy wrapped in pastry.

Do you ever worry that our human faculties may be so limited that our perception of our universe may be merely a model that satisfies us, that we can find a truth that is satisfactory and are never able to peek further and see the reality? Our reality is what fits us best. Is that enough? Could it be possible that other intelligent life that has evolved in different environments has gathered together rules and laws that also fit their experience but are far from our own laws and theories? Oh, and while we are here, my monkey brain is having problems with String Theory, should I persevere or is it all going to be considered outlandish and impossible before I get anywhere near understanding what it is?

B: I don't worry about whether our theories are models or not, although I do tend to think of them as models. Einstein's General Theory of Relativity, for example, is a theory of 'spacetime', often described as the fabric of the Universe. Unlike Newton's Law of Universal Gravitation, gravity is not a force between massive objects in Einstein's theory; rather it is a consequence of the distortion of the fabric of the Universe due to the presence of massive objects. Here we have two models, with very different pictures of the nature of gravitation. Einstein's model is 'better' than Newton's in the sense that its predictions agree with observation more accurately than Newton's. Is either theory a description of how nature *really is*? Probably not; we expect that there should be a quantum description of gravity which involves the force being carried between stars and planets as a stream of particles called gravitons. Such a description would align our model of gravity with our models of the other three fundamental forces of nature contained in the Standard Model of particle physics. Would such a theory be the ultimate model or a description of nature as she really is? Who knows? Our scientific theories allow us to understand what we see, make predictions and make measurements of things such as the age of the Universe. They are also useful; they allow us to extend our lives and enjoy richer and more exciting lives. I don't feel the need to see science as anything more profound than that.



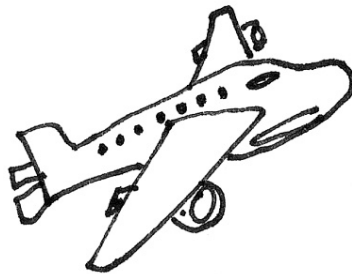
To address your other point, I do not think a civilisation at some other place in the Universe will have a radically different picture of nature than we do. They may have different models, but whatever their model of gravity, it will simplify to something approximating Newton's laws for the case of planets orbiting stars. Whatever their model of atoms, it will describe how hydrogen atoms radiate light with a wavelength of 21cm. Whatever their model of chemistry, it will explain how hydrogen reacts with oxygen to produce water. All intelligent civilisations across the observable Universe are part of and live within the same reality. They will make predictions that are approximately in accord with each other even if their models are different, just as Einstein's and Newton's models make very similar predictions for the orbits of planets around stars.



All monkey brains have problems with String Theory, because we don't possess a fully developed String Theory in the sense that it can make predictions that can be tested by observation. This may be because we

haven't developed the model well enough yet, or that, as you indicate, we might not be clever enough to ever develop the model. It may also be that String Theory isn't the right track at all. We don't know.

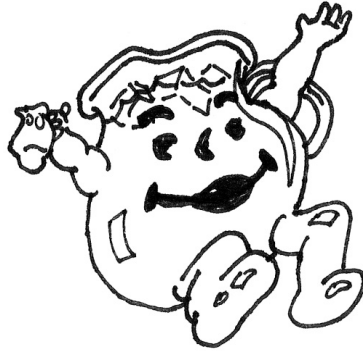
R: I think I will accept that I am certainly not clever enough and will continue on the possible chess-playing abilities of squid for the moment. Would you ever consider that, as 'pattern seeking creatures', we may be fitting our theories into the patterns that satisfy our minds? Could we be blind to other possibilities? Would it plague you if you started to believe that the limitations of the human mind meant that you could only see reality up to one level and that there was a possibility that other creatures had or would evolve that could truly comprehend the Universe?



B: We have been able to develop models that allow us to do wonderful things like medicine and genetic engineering and flight and computing and, ultimately I hope, to become a spacefaring civilisation and disperse our descendants amongst the stars. That's enough for me. I believe that seeking 'the truth' is a fool's errand, and no good has ever come of it.

R: I agree. Never trust someone with an absolute truth, they always want to take over the world and make you drink Kool-Aid. I'll go with a transient reality that gives us better cures for the plagues and better views of Mars.

B: We appear to have converged on the substantive point, which is that anyone who claims to know the absolute truth, whatever that may mean, is at best misguided, and at worst dangerous.





An artist concept of NASA Mars Global Surveyor MGS flying over Mars.

ANOTHER ARGUMENT

Simulation

One of the most recent and most controversial *Monkey Cages* addressed the highly topical and, to some, bizarre question: Are we living inside a computer simulation? The idea was that all of us, and possibly the entire Universe, are simply part of a program being run on some advanced, post-human civilisation's computer – perhaps to model their own history, perhaps to see what happens if you change the course of history. 'I know what happens if we make a reality TV star President of the most powerful nation on planet Earth', for example... 'oh yes, okay, let's not do that'.

This idea triggered an argument between us within minutes of the start of the script meeting. One of us thought it sounded like total nonsense, the other thought that it was a completely logical assumption and if you looked at the maths, it was clearly perfectly obvious, and why couldn't the other one see that? 'Mmm, I wonder which one is which?' we hear you ponder. Although we did eventually calm down (Brian had a pie, Robin went for a brisk walk), we thought that in the interests of world peace and intellectual enquiry, we should have another, less energetic, go at debating some of the mind-altering questions raised in the programme. Questions like:



Are you just the coding of a teenage programmer who has created this universe in his bedroom during a brief break from haranguing the mainstream media and using terminology such as 'snowflake' and 'fake news' on Twitter version 10^{16} ?

If so, will it make any difference to your existence?

If we believe we are living inside a computer simulation, do we start to lose responsibility?

Don't blame me for all that destruction, blame the coder.

And is tech billionaire Elon Musk right when he says that there is only a one-in-a billion chance that we are not in a simulation?'



Here we go again...

ROBIN: When logic enters the room, my irrational and chaotic mind is like paper cuts to Brian's hot-blooded, cold-hearted science brain. I think I am asking quite reasonable questions and he hears a confused explosion of doggerel and limerick partially spoken in Esperanto. The row involved an equation.

How often it involves an equation...

My gut instinct – and I am aware that I should not trust that as I have seen the adverts reminding me that there are bad bacteria as well as good in there, and who's to tell if I am listening to the right bacteria? – is that the idea that there is a one-in-a-billion chance we are NOT living in a simulation is balderdash. Nick Bostrom's 2003 paper, 'Are You Living in a Computer Simulation?', *Philosophical Quarterly* (2003) Vol. 53, No. 211, pp. 243–255, has an equation for the fraction of all observers with human-type experiences that live in simulations:

$$f_{sim} = \frac{f_p f_i \bar{N}_i}{(f_p f_i \bar{N}_i) + 1},$$

Where f_p is the fraction of all human-level technological civilisations that survive to reach a post-human stage, f_i is the fraction of post-human civilisations that are interested in running ancestor simulations, and \bar{N}_i = the average number of ancestor simulations run by such post-human civilisations.

My question was merely ‘is there really any way that you can use this equation to state it is extremely likely we live in a simulation?’

And that’s when it kicked off.



BRIAN: Equations like this provide a framework for thought. In Bostrom’s paper he argues that at least one of the following propositions is true:

- 1. the human species is very likely to go extinct before reaching a ‘post-human’ stage;*
- 2. any post-human civilisation is extremely unlikely to run a significant number of simulations of their evolutionary history (or variations thereof);*
- 3. we are almost certainly living in a computer simulation.*

The equation allows for an estimate of probability, under certain assumptions – it is part of the argument that justifies the claim that one of the above three propositions must be true. The paper isn’t a prediction that we are living in a simulation. Rather, it argues that IF you accept certain assumptions, you are led logically to one of the above conclusions. The assumptions are grounds for debate. You can see, quite trivially, from the

equation that if \bar{N}_i is very large, which is to say that at least some sufficiently advanced civilisations will run a large number of simulations of reality, then in order to avoid the conclusion that f_{sim} is very close to 1, either f_i or f_p must be zero. Put simply, once a civilisation starts to run large numbers of simulations of reality, the overwhelming majority of conscious ‘beings’ that experience the Universe as we do are inside simulations, therefore it is statistically very likely that we are simulated.

What reasons could there be for a civilisation never to run simulations? We must accept that a civilisation can, at some point, gain access to effectively unlimited computing resources, and would choose to use a fraction of these resources to run situations.

This contains the assumption that it is possible for civilisations like ours to progress to technological maturity, or to a post-human phase as sometimes described. One could argue that this doesn’t happen – perhaps technological civilisations are never able to deal with the challenges of, for example, nuclear weapons. Science and engineering always run ahead of politics and morality, and the phase we are currently in is pretty much as advanced as it ever gets. In this scenario, which is sometimes termed the DOOM hypothesis, civilisations inevitably destroy themselves, and we are forced to choose proposition one because we should not assume that whilst all other civilisations destroy themselves, we will be wiser.



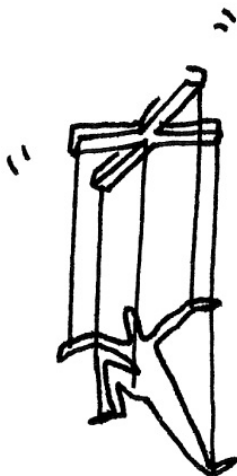
We might also call this the Donald hypothesis.

We must also consider the possibility that it is not possible for conscious entities who experience the world as we do to exist in these simulations. This is the claim that our conscious experience is something that cannot, even in principle, be simulated in some sort of future computing device. If you believe this to be the case, you’d choose proposition two. You would also choose proposition two if you believe that ALL civilisations that have

the computing power to run ancestor simulations decide not to. Maybe you think that this would be a colossal waste of resources, but is it credible to attribute such motivations to ALL civilisations?

If you choose neither one nor two, you have to choose three. The final line of the paper expresses the argument succinctly:

‘Unless we are now living in a simulation, our decedents will almost certainly never run an ancestor simulation.’

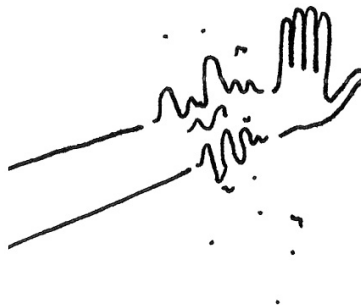


You could, of course, also argue with the logic contained in the paper, but this is best achieved with your brain, and not your gut.

R: Isn't this philosophy rather than science? Why must we accept that a civilisation can, at some point, gain access to effectively unlimited computing resources? What if all the other civilisations of the Universe are not dabbling in computer technology? Isn't there a problem that these sort of fanciful fables are given far too much credibility when there is nothing to base them on apart from a dream and an equation, and then they get bandied around by charlatans and cult leaders and everyone goes insane thinking they are the product of a programmer? Isn't the reaction similar to the reaction of those people who watched *The Matrix* and left the cinema saying, 'wow, that really made me think?', as if they had never bothered to think before?



Is this God for people who like to think they are scientific thinkers but fancy bowing to an altar made of transistors?



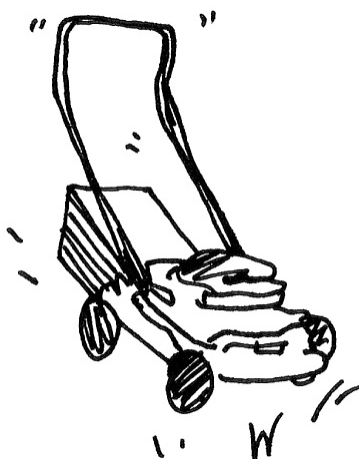
B: The question ‘is this philosophy or science?’ seems to me to be semantics. We are asking a question about the nature of reality. Call it whatever you want. I suppose one could argue that the debate becomes a scientific one rather than a philosophical one when there are predictions which can be tested by observation. Some people have argued that a simulation may be detectable; perhaps there will be glitches in it, or the world will be seen to be digitised in some sense.

The paper contains an argument that it is possible in principle for a civilisation to build powerful-enough computers to run large numbers of ancestor simulations, and I think the argument is sound. This isn’t the biggest problem with the logic.

Your question about charlatans and cult leaders is interesting. You are implying that we should impose boundaries on human thought because

there are those amongst us who are not equipped to handle challenging ideas. I've heard this argument many times, usually from television executives.

My answer is that we should aspire to create a society in which everyone is equipped to debate the great existential questions without fear. Such a society can be created if we treat education as an end in itself rather than a means to produce cannon fodder for our economy. The goal of education is to make no thoughts dangerous.

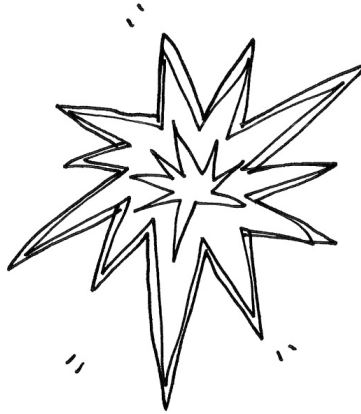


R: I agree with your aspirations, but worry that mass communication has allowed people to spread misreading of ideas with incredible speed. There are people who have proposed that because there is a genetic component to intelligence, we should rethink the education system with the possibility of streaming people after a swab. This seems to return to nature versus nature when every geneticist I know – and I am always hanging around them in the hope they can reorganise my double helix and turn me into the Lawnmower Man – makes it clear that nature is expressed and changed through nurture.

You can't just say

'ah, you've got those genes, that's you done for.' What do we do?

Shall we just ask the BBC for more Monkey Cages? Could that help?



B: It is overwhelmingly likely that in many simulations *Monkey Cage* is valued so highly by the BBC that it is a weekly fixture on both radio and television, and does indeed contribute to a more enlightened society. The programmer of our particular simulation seems to have wanted to explore a less-enlightened timeline.

On a more serious note, regarding the Donald hypothesis, I find it ironic that we can save our place as ‘real’ beings inhabiting the base reality of the natural world, but only if we assume that we are so stupid that we will destroy ourselves before we reach technological maturity.

SCIENTIFIC METHOD

If science is so good, why do they keep having to change it?

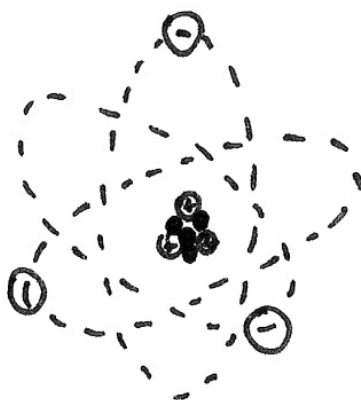


‘If science is so good, why do they keep having to change it?’ asked a journalist, seemingly affronted by the reduced levels of pain experienced during dental treatment and the lack of cholera symptoms in the high street. Warming to the topic, he superciliously sneered,

‘Scientists haven’t even worked out how the Universe began! Why is it taking them so long to find the answer? Surely it can’t take that long to work out why everything exists?’



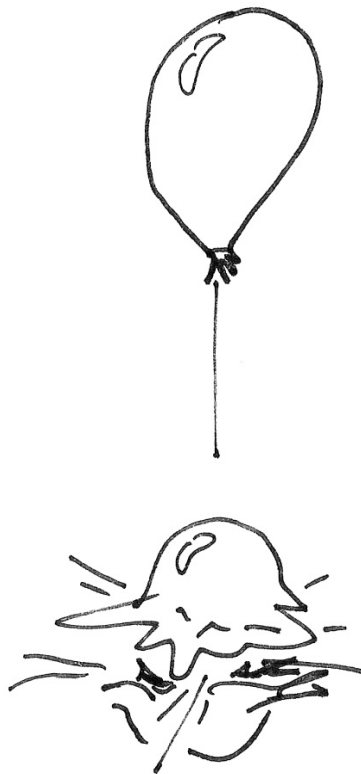
To be fair, it is a pretty big question. The journalist seemed to think that the easiest question must be the first one, and therefore understanding how everything began must be a prerequisite for understanding anything at all. This is a misunderstanding. How do fleas jump?³ Why is the Sun hot?⁴ Do the Lorentz transformations allow all the results of time dilation, Lorentz contraction, the relativistic Doppler effect and the velocity addition formula to be derived?⁵ All these questions are easier to answer than ‘where does everything come from?’



This raises an important point about science which is a critical component of its success.

Science is not an attempt to derive everything from first principles. It is not a search for ultimate truth. Our explanation for the origin of the Sun’s heat

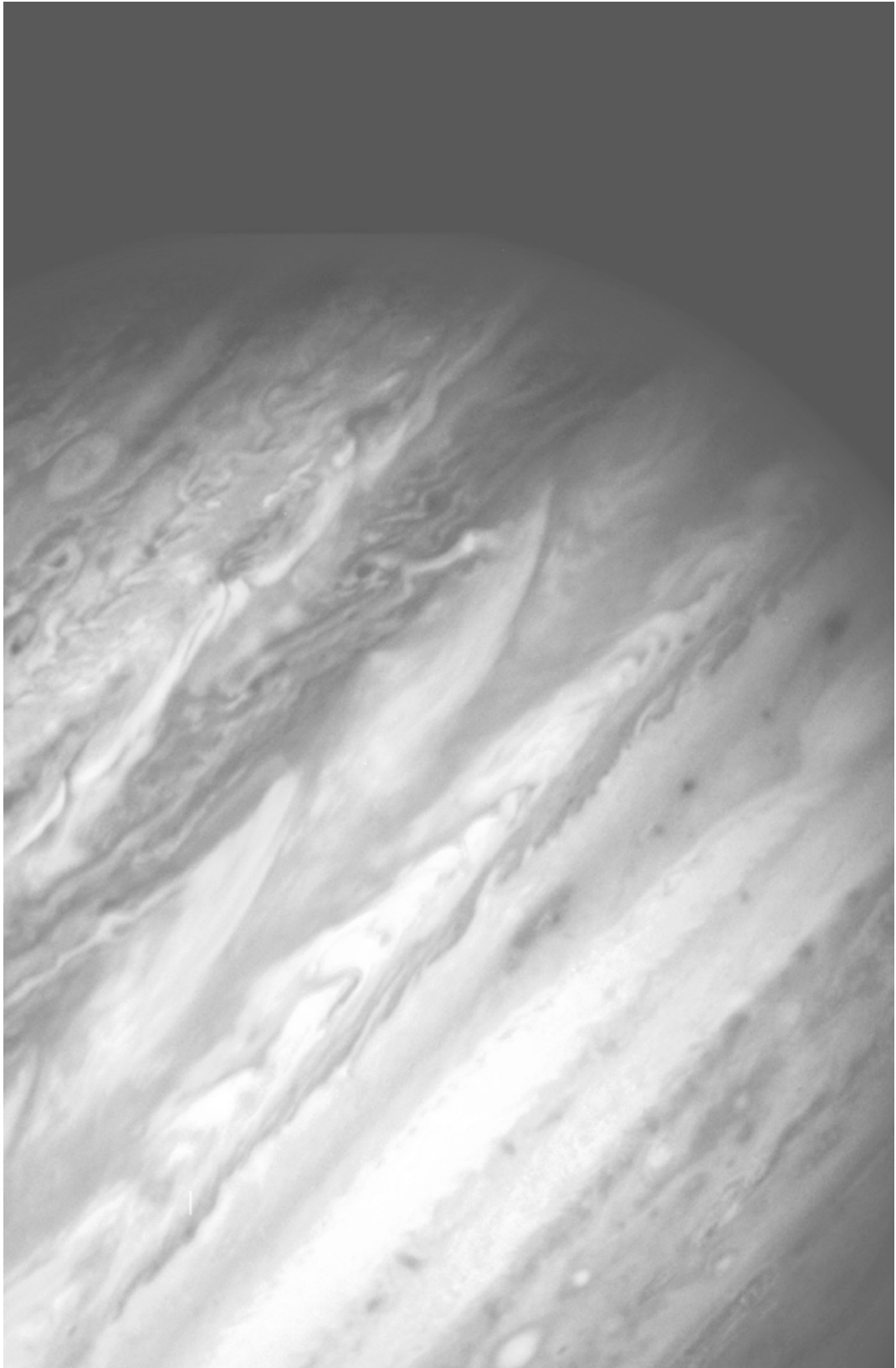
in footnote 4 requires that we accept that protons and neutrons exist, and that we understand how all four forces of nature work in the conditions present inside the core of the Sun. We do not need to explain the origin of the protons and neutrons, although we know that they were synthesised from the quark-gluon plasma that existed during the first few seconds after the Hot Big Bang. We could continue and ask where the quarks came from and, more tentatively, we can answer that they came from the decay of inflaton particles which appeared as a cold gas at the end of inflation (see [Recipe for our universe](#)). How and when did inflation start? We don't know, but we don't need to know to be able to answer the question 'Why is the Sun hot?' If we were *only* interested in a complete understanding, we wouldn't be happy with the answer. We might be tempted to discard it, but that would prevent us using our knowledge of nuclear and particle physics to do other things; medical imaging, for example, or proton beam therapies for cancer treatment.



Scientific explanations are different to philosophical or theological positions in that their worth is judged primarily by how useful they are, and not by their logical completeness or aesthetic value.

All scientific theories or explanations that we currently possess require us to accept something; somewhere in the chain of logic, the most exciting phrase in all of science will appear:

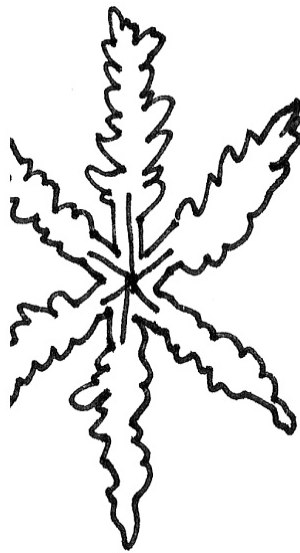
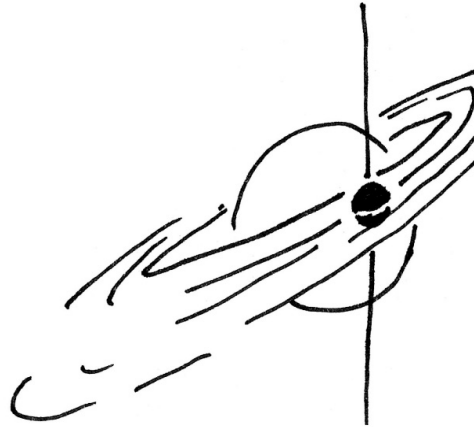
We don't know.



The NASA Hubble Space Telescope shows detailed analysis of two continent-sized storms that erupted in Jupiter's atmosphere in March 2007.

Look at Saturn through a telescope, for example. You'd think we'd at least know why it has those rings, but we don't. One theory is that the rings formed when a large moon became disrupted by gravitational tidal forces as its orbit decayed and it drifted inwards towards the planet. We are familiar with tidal forces on Earth – the differential gravitational pull of the Moon across the diameter of the Earth is responsible for the ocean tides, but the Earth also exerts a gravitational tidal force on the Moon. This distorts the satellite and raises a tide of around 50cm in the lunar rocks, heating up the Moon very slightly through friction. For the Earth–Moon system these effects are small, but in the Jovian system things are greatly amplified. Jupiter is 318 times more massive than the Earth, with a correspondingly larger gravitational pull. Its innermost moon, Io, is roughly the same size as our moon and orbits at roughly the same distance, but because of Jupiter's much greater mass and the presence of two other nearby moons, Europa and Ganymede, it tears around the planet every 1.7 days in an elliptical orbit and experiences extreme tidal forces. In places, Io's surface rises and falls by over 100 metres over the course of an orbit, leading to extreme frictional heating and making Io the most volcanically active body in the Solar System.

There is a limit to how close a moon can get to a planet before the tidal forces rip it apart, or prevent it forming in the first place, and this is known as the Roche limit. Saturn's rings are almost entirely inside the Roche limit, with the exception of the E-ring, which is thought to be created from material ejected from the active moon Enceladus that orbits within it. It is possible, therefore, that an intact moon changed its orbit, perhaps due to an interaction with other moons or a collision, drifted inside the Roche limit and disintegrated to form the rings. Another theory is that the rings are leftover material from the formation of Saturn, and because the ice and dust are inside the Roche limit, they never coalesced to form a moon in the first place. Such an origin would suggest that the rings are as old as the planet.



A competing theory is that the rings are young relative to the age of the Solar System. The rings are made primarily of water ice, which is why they are so bright and easy to see in a very small telescope from Earth. The Solar System is a dirty place, however, full of dust and debris, and ice doesn't stay pristine for long. By measuring the proportion of rocky silicate particles in the rings, astronomers can estimate their age, and this has been done using data from the orbiting Cassini spacecraft. A recent analysis suggested an age of between 15 and 100 million years, which may mean that they did not exist when dinosaurs walked the Earth. None of the theories for the formation of the rings described above would fit easily with such a recent origin, and so the debate continues. This doesn't mean that we know nothing about planetary ring systems. It means that trying to work out how things formed many millions, or even billions, of years ago is hard.

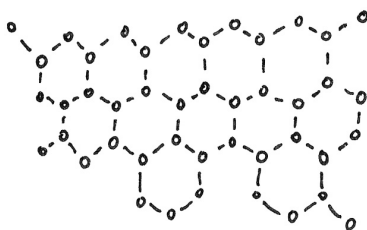
As we write, the Cassini spacecraft is nearing the end of her Saturn mission by repeatedly diving in between the rings and the planetary surface, gathering data and taking spectacular photographs. New data, coupled with new theoretical understanding, may solve the problem of the origin and age of Saturn's rings, or it may not, but this is the best we can do at present. This is a good way to think about science. It does not hold all the answers, and the current theories may be wrong, but the *scientific* debate represents a snapshot of our best understanding of a problem (to which science is applicable) and our uncertainty at any given time.

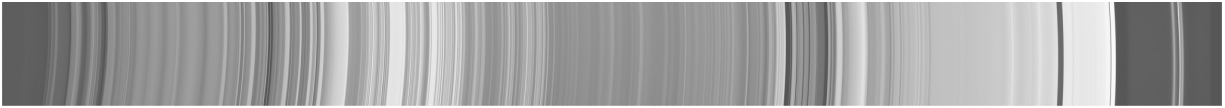
For those with an enthusiasm for science, its incompleteness is a delight. There is always work to be done. Each new theory or observation is a plank in the bridge that will lead to enhanced understanding, but complete understanding is a chimera because the other side of the ravine is not immovable. The geography changes with each new discovery. When a theory is confirmed, the research does not end. Changes in technology and thinking lead to adaptations in interrogation methods and new data. The best response for now is:

'Great news, we've reached an answer.'

'Excellent, can we close the big book of Science?'

'I'm afraid not, it seems that out of the solution more questions have grown.'





Saturn's rings, imaged by the Cassini spacecraft in a series of 45 photographs on 9 May 2007 (<https://photojournal.jpl.nasa.gov/catalog/PIA08389>). The Cassini Division can be seen with a small telescope from Earth. The delicate structures in the rings are all gravitational in origin and result from the 60 large moons that orbit outside the rings and the hundreds of smaller rocks and mini-moons (called Shepherd Moons) that orbit within them. The inner edge of the Cassini Division, for example, is created by an orbital resonance with the moon Mimas. A particle in the rings at this distance from Saturn would orbit twice for every single orbit of Mimas. It would therefore line up with Mimas every second orbit and get a gravitational kick, knocking it into a different orbit and clearing a gap.

Why, then, was our journalist friend so antagonistic towards, or threatened by, science? The answer may be that some people crave certainty. If the answer to the question 'are you sure?' is 'no, but...', such a person may have already begun to wander towards the wizard on the rock who claims to have the ultimate, unassailable truth.

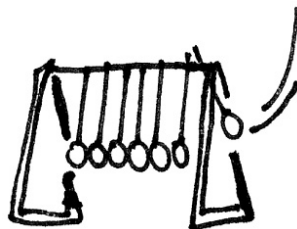


Psychologists call this basic human need *cognitive closure*. It is quite natural, and we all experience it at some level; we can't relax until we

receive our exam results, for instance. But for some people, the need for a complete and consistent world view can become overwhelming, and such thought patterns are known to be common in people attracted to religious fundamentalism and other extremist ideologies. The world *is* complex, the future *is* unpredictable, and our knowledge *is* incomplete. These statements are self-evident and a source of joy to the scientific mind, because the scientist is in the business of adding to knowledge, which by definition requires an acceptance of its incompleteness. This may be why the certainty of many political and religious positions is so hard to understand for most scientists, and why science can appear so unsettling and provoke such a violent reaction in people who have an extreme requirement for cognitive closure.



Somewhat paradoxically, the necessary uncertainty at the heart of science may be reassuring for those who consider its findings uncomfortable. After all, if the only thing worth believing in is absolute truth, science isn't worth believing in. Evolutionary theory, climate science, the Big Bang, or anything that conflicts with a world view constructed to deliver cognitive closure can be easily dismissed. 'But scientists got this wrong and this wrong, so why believe them now?'



Isaac Newton was wrong, though he was also right... up to a point. His laws may break down at speeds close to the velocity of light or in stronger

gravitational fields (including the orbit of the planet Mercury), and Einstein may have usurped him, but Newton's equations remain effective enough to be used to get humans to the Moon. In the leagues of being wrong, Newton is in the lower divisions.

There was much excitement recently when the OPERA experiment (Oscillation Project with Emulsion-tRacking Apparatus) appeared to observe neutrinos travelling faster than the speed of light. This would have violated the laws of physics as we understand them today. Had it been true, it would have triggered a major effort in theoretical physics to explain the results.

Professor Jim Al-Khalili promised to eat his underwear if it was true. Brian had a vague glint in his eye; it seemed unlikely, but if so, what exciting times in which to live.



In the end, the anomalous result turned out to be a fibre-optic cable that was wrongly connected. Some scientists felt that the OPERA experiment had published too early and had thus given succour to those who wish to denigrate the processes of science. But another view, which we share, is that the episode showed science in action. If the result of an experiment contradicts the accepted world view, that is certainly not a reason to withhold publication. As an experimental scientist, if you cannot see

anything wrong with your data, you should publish and allow others to cross-check, challenge and perhaps repeat your experiment. They may well find an error, but this is how science moves forward. Every error teaches us a little more about experimental technique, or if we are lucky, something deeper about nature.

‘If people didn’t sometimes do stupid things, nothing intelligent would get done,’ wrote Ludwig Wittgenstein, a man who had Bertrand Russell crawling on all fours trying to prove that it was possible to be certain that there was no rhinoceros in his office, entirely missing the elephant in the room. Scientists should not shy away from being seen to be wrong. Dictators don’t like easy access to evidence and easy access to jokes.

Both information and laughter are damaging to the reputation of one who projects certainty, but may enhance the reputation of the more humble individual.

It requires an effort of will to choose doubt over certainty. If you are interested in the least-wrong explanation of why we are as we are, with perpetual room for doubt and perhaps a sneaking hope that you will discover a flaw in the currently accepted theories and thus generate even more questions, you will enjoy science. If you require a rule book carved in granite, you will find science exasperating.



The Fable of the Least Wrong

A merchant was picnicking in the countryside with a Dockist ploughman and a Waspist shepherd. Clumsily eating his lolly, his hand was tainted by hundreds and thousands and raspberry syrup. The wasps were alerted to the

potential deliciousness and he was harshly stung. As he yelped and danced, the Dockist Ploughman said, 'you must pour honey in your hand and rub it with a dock leaf, the honey attracts the venom back out of your hand and the rubbing of the dock leaf creates a gravity well which speeds up the withdrawal of the venom.' The Waspist Shepherd was indignant. 'That is utter nonsense. You must get out your sword and strike off your arm before the wasp demon possesses your mind.' Thinking for a moment, the Merchant took out his sword and struck off his hand.



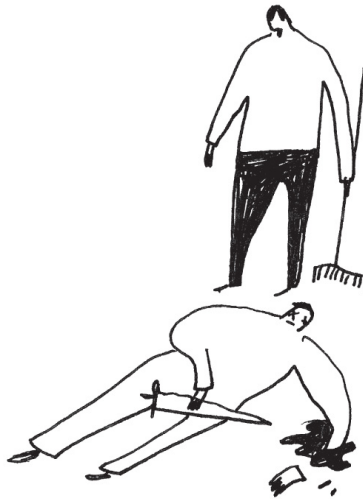
Blood went everywhere and he danced more and yelped more and eventually fell to the ground, initially in shock, and then in death.

'Look what you've done,' said the Ploughman.

'Well, I definitely stopped him suffering that stinging sensation in his hand,' said the Shepherd, as he nibbled away at the remains of the dead merchant's lolly.



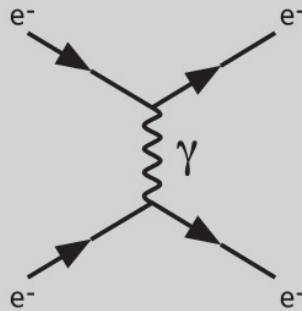
Both the Shepherd and the Ploughman's answers were wrong, but can you work out which was more wrong? (Answer [here](#))



Quantum Electrodynamics

Richard Feynman's most well-known contribution to physics are his eponymous Feynman Diagrams. They are graphical representations of the mathematical calculations required to calculate the probability that something will happen. Feynman first applied his diagrams to the theory of Quantum Electrodynamics, or QED, for which he received a share in the 1965 Nobel Prize for Physics with Julian Schwinger and Sin-Itiro Tomonaga. QED describes how electrically charged particles, like electrons, interact with each other. That may seem to be a restricted ambition, but everything you experience in the world other than gravity and nuclear phenomena (which you don't experience directly) is described by QED. Here is a Feynman diagram showing the dominant contribution to the calculation of the probability that two

electrons will scatter off each other. They do so by exchanging a photon, a particle of light.



ANSWER: On this occasion, the honey and dock leaf version was less wrong as it does less damage than cutting off your arm. Also, though the gravity well theory and the honey were not much use at all, the creation of a moist, cool sap from the crushed leaf may have relieved some of the stinging situation. There is some debate that the alkali content of the leaf will also help neutralise any sting with acid content, such as an ant bite that contains formic acid. Some may argue that cutting off the hand was the most effective cure for loss of stinging sensation, as it would have been entirely replaced by a 'oh my god, I've hacked off my hand' sensation.

WHAT IS IT ABOUT RICHARD FEYNMAN THAT MAKES HIM SO FASCINATING? IS IT BECAUSE HE WAS SO COMPELLING IN EXPLAINING FASCINATION? WAS IT JUST BECAUSE PEOPLE DON'T EXPECT A PHYSICIST TO BE A CONCERT LEVEL BONGO PLAYER?

I DON'T KNOW WHY THIS SHOULD BE SO UNUSUAL. I KNOW PHYSICISTS FROM ROCK BANDS.

HE HAD A NEAT LINE IN APHORISMS, TOO.

Physics is like sex. Sure it may give some practical results but that's not why we do it.

HIS FATHER ALWAYS ENCOURAGED RICHARD TO BE A SCIENTIST. HE EXPLAINED TO HIM THAT KNOWING ALL THE NAMES GIVEN TO SOMETHING BY DIFFERENT PEOPLE OF THE WORLD TOLD YOU NOTHING ABOUT THAT THING.

but in Spain this golden frog is called "Rana venenosa de oro" and in French.

It would be better if he knew it was the most poisonous frog in the world.

SOMETIMES HIS QUESTIONS WERE ABOUT THE VERY FOUNDATIONS OF THE UNIVERSE. SOMETIMES THEY WERE ABOUT JELLY.

I just started to wonder, could jelly set if constantly stirred at sub zero temperatures?

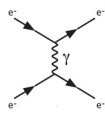
FEYNMAN WORKED ON THE MANHATTEN PROJECT DURING WORLD WAR 2. WHEN THE ATOM BOMB WAS DROPPED ON HIROSHIMA, THE SCIENTISTS CELEBRATED.

COLDEST DAY OF THE YEAR

What are you doing?!

HE NEVER PUBLISHED. WE STILL DON'T KNOW. PLEASE EMAIL US ANY RESULTS YOU HAVE. GET PLEASE ONLY LEAN OUT OF SECOND FLOOR WINDOWS.

A Feynman Diagram



LEAVING A RESTAURANT IN NEW YORK, FEYNMAN WAS STRUCK BY THOUGHTS OF THE MAGNITUDE OF DESTRUCTION THAT WAS POSSIBLE.

IN 1965, FEYNMAN SHARED THE NOBEL PRIZE FOR HIS WORK ON QUANTUM ELECTRODYNAMICS.

THEY'RE CRAZY. WHY ARE THEY BUILDING NEW THINGS? IT'S SO USELESS.

RICHARD'S YOUNGER SISTER IS A PIONEERING ASTROPHYSICIST. WHEN THEY WERE YOUNG, THEY SAW THE AURORA BOREALIS AND MADE A DEAL. RICHARD COULD HAVE THE REST OF THE UNIVERSE BUT THE AURORA WAS JOAN'S.

THE PUBLICATION OF SURELY YOU'RE JOKING, MR. FEYNMAN IN 1985 BECAME A BESTSELLER.

ADVENTURES OF A CURIOUS CHARACTER

FEYNMAN WAS BROUGHT IN TO SIT ON THE COMMITTEE TO INVESTIGATE WHY THE CHALLENGER SPACE SHUTTLE GLEW UP.

The Orings lost their elasticity when it was cold, so they were no longer effective.

FEYNMAN DIED FROM CANCER COMPLICATIONS IN 1988.

WE LOVE YOU DICK

I'd hate to die twice, it's so boring.

©NATALIE KEY-THATCHER

Here's one of Feynman's diagrams, of an electron emitting a photon, which is absorbed by another electron. See previous page for further notes.

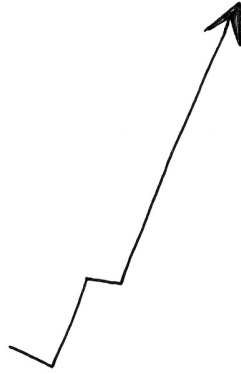
ROBIN'S THOUGHTS

On reading about science

Despite what you might imagine, understanding all of science can take time, and even that depends on whether time actually exists. For now, though, we will accept that time exists – at least for the next few hundred years.



A few thousand years ago, it was much easier to be wise. You didn't need to know nearly as much to know everything. In the last couple of hundred years, knowledge of our universe and conjecture of others has grown at a stupefying rate. You have to choose your questions carefully and work in small corners. Veer from your speciality and there is danger of misunderstanding at every corner. Do not rely on a scientist who understands the quantum effect that creates Hawking radiation that escapes from a black hole to have the slightest clue about the Komodo dragon's ability to procreate via parthenogenesis.



When daunted by cosmologists at cocktail parties, I have frequently found that my ability to ask salient questions about reptile reproduction and their confusion and inability to answer even the simplest questions on the mating behaviour of the Galapagos tortoise has helped increase my confidence.

When I met the Nobel Prize winner Peter Higgs, I knew that I had little to offer conversationally, save for the information that playing a B-flat on a French horn will stop an attacking crocodile in its tracks (it may also work with a cello, but this is harder to hang off your rucksack).

When your experience of science comes only from the classroom in your teenage years, returning to it years later can be daunting. You are attracted to a book on the '3 for 2' table of your local bookshop. It promises to tell you 'everything you need to know about the quantum universe'. It is even described as 'for the interested lay person'.

Some days later, your head covered in a towel as you breathe camomile steam out of a bucket in a desperate bid to clear your head and see if there is any way you can continue to function in this now probabilistic universe, you rue the day you picked up that book.



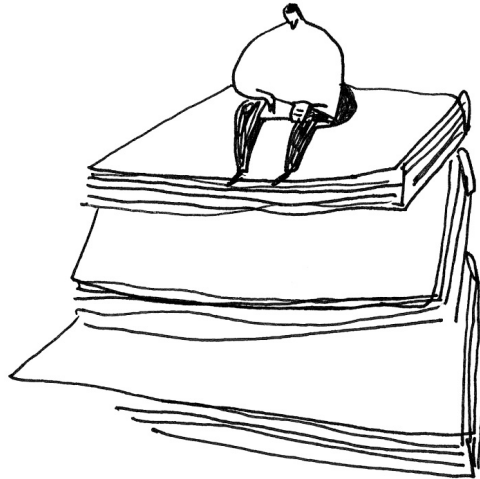
What an idiot you are, you read the whole book and still you don't have a deep understanding of Heisenberg's uncertainty principle and black body radiation. One of the problems with reading science books for the first time, or even returning to them after a long break, is that people can very quickly presume they haven't understood enough and therefore must not have a science brain.

This is not true.

Do not expect to read one book about quantum cosmology, put it down, and become a professor. There is a reason why so many people work on the same problems and frequently approach them perplexed, and sometimes depart from them perplexed. Even in popular science books you will come across words and ideas that can be both tricky and counter-instinctual. I don't think I had read 'inculcate' until 2007, but since then it's in almost every book I read. 'Phenotype', 'genotype', 'eukaryotic', 'quark' and 'planemo', there is a language rich in words that are infrequently overheard in commuter-train phone conversations and barroom banter, unless you have been very picky with your pub (and you should be. I wait for the pub that promises 'Big Screen Attenborough' rather than Big Screen Sports).

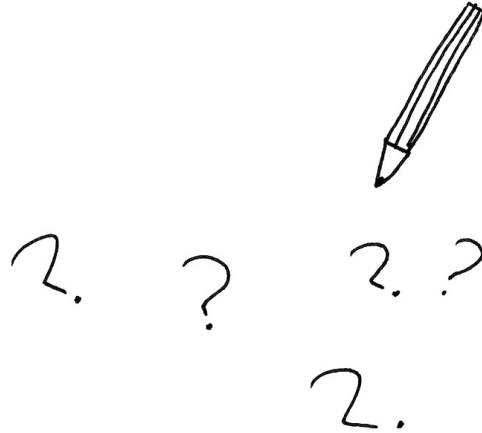
Those 'he said, she said' conversations are so much better if they are:

'He said, he accepted conventional cosmology with a universe ending after perpetual expansion until all the stars and matter are no more and it's just dominated by cold radiation. And she said that she was increasingly drawn to Penrose Cyclic cosmology, so he said...'



Reading science books requires a change in the reading style for an interested but unsure non-scientist. It's hard to race through them at a John le Carré rate of thrills and suspense. You need to slow down your reading and contemplate the meaning of the descriptions.

Gazing out of a window with a knitted brow or perplexed squint can be a major part of reading books on physics. It is worth it when you get the little explosions of comprehension. Some people choose to read to incomprehension and beyond, then go back to the start. Others read until flustered and then go back, hoping each time to get a few pages further. Bibliophiles may splutter, but keep a pencil handy for underlining and making notes in the margins (those who view their books as religious scrolls may use Post-it notes). This also makes the book an intriguing artefact of your life. It becomes a palimpsest and is also a treat for those who may buy your book secondhand. My copy of Colin Blakemore's *Mechanics of the Mind* is not merely precious because of his words, but also the words of the presumed ancient academic with a spidery scrawl in the margins and other gaps. From page one, this reader was in an obstreperous mood. Words considered extraneous are crossed out, sometimes with the addition of an exclamation mark or other inky systems of conveying a 'harrumph'. By page nine, the reader is cross enough to write, 'he doesn't even understand the science of buttered toast'. On page 53, he has had enough: 'I'm going to stop reading now!' But he didn't, and the trail of his mind is left throughout the book.



This is the beauty of books, they are secondary human fossils. We may leave behind bones, skin preserved in a peat bog, perhaps eventually a fossil, but books are our mind fossils, the fossils of our thoughts that are left after we have gone. We appear to be the only creature that can interrogate minds even after the owner of those thoughts has died.

Be patient when reading science. It may take you a few weeks to finish that book on epigenetics or black holes, but it has taken the scientists working on those subjects decades to get to this point of understanding. Don't be surprised if the three-hundred-page summary of years in laboratories, facing wipe boards and listening to radio telescopes takes a while to permeate your mind.

If you go into it thinking 'I expect to understand the Universe by the end of June', you may be disappointed, if you enter into it with a desire to be excited by brief explosions of understanding mixed with awe and a perplexed delight, you'll be able to counter bewilderment.

You may keep reading for the rest of your life and never win a Nobel Prize, but hopefully, at the end of each week, as you look up at the sky, across to the sea, or at your own children, the Universe and its possibilities will look slightly different to the way they looked the week before.



¹ Brian: I object to the name of the campaign. It should be 10^{23} , which refers to Avogadro's number – the number of constituent particles in one mole of a substance. By suppressing the notation, I think we are dumbing down the art of campaign-naming. In any case, Avogadro's number is $6.022140858 \times 10^{23}$, which should be rounded up to 10^{24} . So the campaign, even if we allow for dumbing down, should have been called 10:24. But I don't like that notation.

² Please be aware that despite using the term 'next', the authors of this book cannot guarantee that time is linear.

³ This is a good question, and one that has been argued over in literature for many years. There were two different hypotheses: fleas jump by pushing off from their knees (or, more accurately, their trochanter) or their toes (the end of the tibiae). In a seminal paper published in 2011, Sutton and Burrows concluded that the second hypothesis is correct: 'Fleas jump by applying forces to the ground through the end of the tibiae.' Sutton and Burrows, *Journal of Experimental Biology*, 2011, 214: 836–847.

⁴ The Sun shines by converting hydrogen into helium in its core. A hydrogen nucleus consists of a single proton, and a helium nucleus consists of two protons and two neutrons. Protons can be transformed into neutrons through the action of the weak nuclear force. A helium nucleus is very slightly less massive than four protons, and the missing mass (26.7 MeV) is transformed into energy in accord with Einstein's famous equation $E = mc^2$. Of this energy, 98 per cent is carried away as light – which is why the Sun shines – 2 per cent is carried by neutrinos. As an aside, there are around 100 billion neutrinos passing through each square centimetre of your body every second from the nuclear reactions in the Sun. The detection of these neutrinos was one of the final pieces of experimental evidence that confirmed the details of the nuclear fusion reactions deep inside our star.

⁵ Yes.



THE END IS NIGH

(sort of)

Hopefully by this point in the book you are beginning to come around to the idea that there are no certainties, only probabilities, and this may give you some solace when it comes to discussing the end of it all. That 'all' may include the end of your conscious existence, the end of the Earth's existence, and the end of our universe.

It is hard to imagine the world without us. It is even harder to imagine a universe without any humans whatsoever, or a future where there is no planet Earth, no Sun, and eventually nothing discernible and nothing to

attempt to discern it. There is no way around this, so with a spoiler alert we have to tell you, the extinction of the Earth is inevitable.

It will not take a Vogon Constructor Fleet to incinerate the Earth, it will take the swelling of the Sun into a red giant in a few billion years.

When we imagine the destruction of the Earth, we are most disturbed if we think we will face it in our lifetimes. The good news is that, so far, every apocalyptic prediction in history has failed to come to fruition.

In 2012, we waited for the Mayan prophecy of the end of the world to take us. We even managed to persuade D:ream to re-form for the occasion (one of us has an 'in' with the band). At our special 'this will be the last show you will ever see, refunds will be available in the foyer afterwards' at the Hammersmith Apollo, as the glitter cannons fired and 'Things Can Only Get Better' reached its crescendo, it appeared the Earth was still rotating.



To be fair to the Mayans, it seems the merchants of doom (scam publishing division) may have been misconstrued. Like so much doom-mongery, the inevitable had its inevitability reduced as the days of reckoning approached, which also allows for follow-up volumes describing exactly when Doomsday will occur. This is a relief to our editor at HarperCollins.



Other Ends of the World that haven't happened as yet, but have been predicted by Hollywood, include:

- A gilled Kevin Costner living on an action raft.
- Kevin Costner being your postman.
- A big tidal wave on its own.
- A big tidal wave that then freezes and you have to burn all the books in the library to keep warm.
- A big tidal wave and Godzilla coming with it.
- Multiple alien invasions from Mars and beyond.
- Bruce Willis sacrifices himself and prevents a meteorite destroying the Earth.
- Someone else in a very similar film about a similar threat whose name no one can remember, but it was released about the same time, sacrifices themselves similarly.
- Kevin Costner building a baseball diamond in his field and inviting ghosts to play on it who then destroy the world by sucking out the souls of everyone (that part of *Field of Dreams* was eventually cut as it did not play well to test audiences in Denver and St Louis).

What are the real-life perils that may obstruct our progress if we don't manage to make it all the way to the heat death of the Universe in our cosmic thermal underwear?

If you grew up in the 1970s, many of us thought that the greatest threat to our existence was being run over by a combine harvester, or plucking a Frisbee from a power station. The public information films of that era spawned a very paranoid generation.

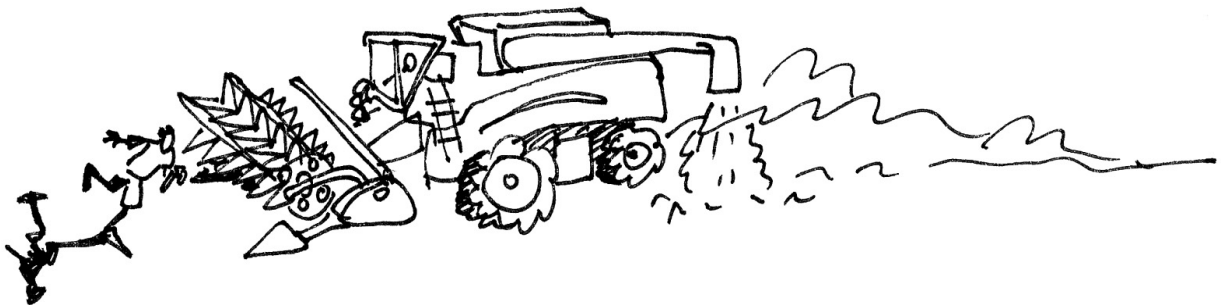
‘Put a rug on a polished floor? You might as well be setting a man-trap.’

Some wives who were particularly bored with their husbands did both.

The dinosaur demise surfaces in the newspapers every five years or so, often in conjunction with a Hollywood release on a similar theme. Will a meteorite impact create a dark, forbidding winter with the only surviving humans mutating into mole people? Or will a combination of lasers and Bruce Willis clones, programmed for jeopardy and devil-may-care risk, create a safety net in our upper atmosphere?

Could the Sun do for us in less than five billion years? Just how dangerous are coronal mass ejections? In 1989, part of Canada’s National Grid was wiped out.

Will a coronal mass ejection destroy the accuracy of your satnav and see the world end in a deafening cacophony of car horns and collisions as people find themselves driving forever around Telford?





The prospect of what happens after we die has troubled us since we became aware of our mortality. We dream of a grand solution. We imagine a vast space liner transporting survivors through the Universe, utilising its warp drive to drop off a menagerie of Adams, Eves and a dove or two on each planet that might support life like ours. Carl Sagan wrote,

‘If the dinosaurs had a space programme, they’d still be around.’

‘Look on my works, ye mighty, and despair’, is the oft-recited line from Shelley’s ‘Ozymandias’, and that is our alibi for not building backyard pyramids or replicas of the Hanging Gardens of Babylon behind the cabbages on the allotment. But don’t let anxiety drown you when thinking about the apocalypse, however it may come. We are an ingenious species with an ability to create solutions for major problems.

There may be no grand purpose to our existence in the Universe, and this may be a good thing. Rather than fulfil a pre-ordained role, we can create our own purpose. If we’re going to go by whatever means – whether minor slip or major cosmological incident – that’s a pretty good motivation to do as much as we can before departure.

And just in case one of fiction’s imagined apocalypses is not our destiny, here are some scientific predictions for the end of days.

NO STARS

‘Electricity is humming. You hear it in the mountains and rivers. You see it dance among the seas and stars and glowing around the Moon, but in these days the glow is dying. What will be in the darkness that remains?’

The Log Lady, *Twin Peaks*



Despite the fact that there are few certainties in science, there is one thing about which we can all be certain: one day, we will die. Perhaps the point of existence is to learn to deal with this inevitability. Our atoms won't disappear when we die; they will be recycled back into the Earth, and many of them will become part of the living things of the future. Reincarnation of a sort, but the atoms will carry no imprint of the past pattern known as you. It is also inevitable that the Sun will run out of fusion fuel in five billion years and cease to shine, and long before that our planet will have become uninhabitable and may even have been swallowed up by the dying star. You and some of the atoms that were once Earth will be ejected out into space, and in billions of years they will become part of new solar systems with their own stories to tell. The great cycle of stellar death and rebirth offers a sort of limited immortality; the atoms that are currently you have already lived through at least one stellar death before ours, and possibly more. Whether that is comforting is up to you.



But what of the Universe? Does it have an end? Probably not, in the sense that it won't cease to exist as far as we can tell. But there will come a time when time has no meaning. The most likely future fate of the Universe, given our current understanding of physics, is a gradual slide into darkness.

In 'The Recipe for Our Universe' we discussed the Friedmann Equation, which allows us to calculate how the Universe will evolve into the future, given its contents now. Today, the Universe is made up of approximately 70 per cent dark energy, 25 per cent dark matter and 5 per cent matter, and the Hubble Constant is around 67 km/s/Mpc. These numbers determine the fate of the Universe.

As the Universe expands, the fractions of dark matter and matter decrease as they become diluted, but dark energy remains constant per unit volume of space.^{[1](#)} In the future, therefore, dark energy dominates and the Universe will continue to expand forever at a constant rate, doubling in size every 20 billion years in what physicists call an exponential expansion.^{[2](#)}



If we survive into the dark-energy-dominated future, way beyond the death of our sun, we will look out into a sky that appears very different from the rich star fields and clusters of galaxies that we

observe today. The galaxies will still exist, but we will be unable to see them.

Recall from 'The Recipe for Our Universe' that the more distant the galaxy, the larger its redshift. This is because the light emitted from the galaxy has travelled through expanding space on its way to us, and the longer its journey, the more stretched it becomes. In the exponentially expanding Universe of the far future, the distance between the galaxies will be so great that, even for the nearest galaxies, the light will be redshifted way beyond the visible and be dimmed by the vast distance. The galaxies will fade from the sky, and beyond our lonely outpost of stars, only darkness will remain.



The stars within our galaxy will still be visible, because they are gravitationally bound together and are not carried apart by the expansion of space. The Milky Way will be larger than it is today because it will have merged with our nearest neighbour, Andromeda, which will collide with us in around four billion years. The only other large galaxy in our vicinity, Triangulum, may also merge with us.

Whilst astronomy will be less interesting in the far future, because we only have a single galaxy to observe, we might at least hope that we could exist forever in our extended island home, but this will not be the case.

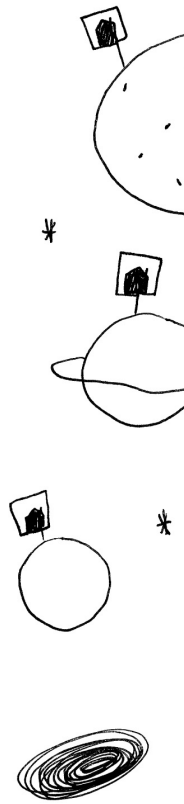
All stars run out of fuel, and when nuclear fusion stops, a star begins to collapse. Some of the stellar matter is returned to the galaxy to form new

stars, but the core is left behind as a faint, fading husk. Stars like our sun will end their lives as a white dwarf, a compressed ball of matter the size of the Earth, but with a density of a billion kilogrammes per cubic metre. White dwarfs resist the crushing force of gravity through a quantum mechanical effect known as electron degeneracy pressure. Electrons obey the Pauli exclusion principle, which roughly speaking means that they aren't allowed to occupy the same volume of space.³ As a dying star collapses, the density increases until the electrons get too close to each other and 'push back', exerting a pressure that prevents the star collapsing further.

For stellar remnants with masses greater than 1.4 times the mass of the Sun, electron degeneracy pressure is insufficient to resist the inward pull of gravity, and the collapse continues. The electrons and protons are converted into neutrons, and the result is a neutron star. These exotic objects are two or three times the mass of our sun, compressed into a sphere the diameter of a city. A matchbox filled with neutron star material would weigh three billion tonnes on Earth. Neutron stars are held up by neutron degeneracy pressure, because neutrons also obey the Pauli exclusion principle, but even this has its limits. For stellar remnants with masses greater than three times that of our sun, there is no known effect that can prevent complete gravitational collapse, and the star becomes a black hole.



The matter in white dwarfs, neutron stars and black holes is locked away and cannot participate in new star formation. In this way, star formation rates in galaxies decrease over time, and eventually no new stars are formed. The last stars to die are low-mass red dwarfs, which range from around one-tenth to a half of the mass of our sun. These stars burn their hydrogen fuel very slowly, because they do not have to release much energy to resist the inward pull of gravity, and consequently have very long lifetimes. The smallest red dwarfs have lifetimes of ten trillion years – a thousand times the current age of the Universe.

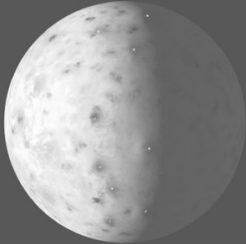
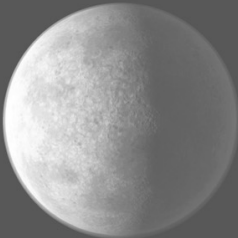
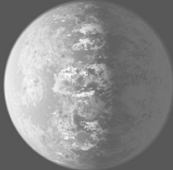



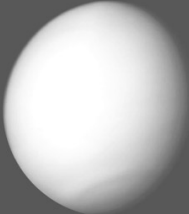
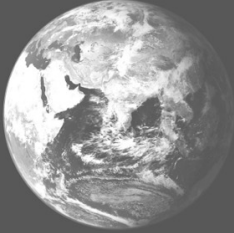
If our descendants persist for hundreds of billions of years, and still require or desire a planet to live on, they will most likely live in a red dwarf system. One of the best candidates might be the TRAPPIST-1 system, just under 40 light years away in the constellation of Aquarius. The star TRAPPIST-1 is a low-mass red dwarf, not much larger than Jupiter but 100 times more massive. It has seven rocky planets in very close orbits, with years ranging from 1.5 to 20 Earth days. The planets are so close to the dim star that at least three are thought to be inside the ‘habitable zone’, which means they

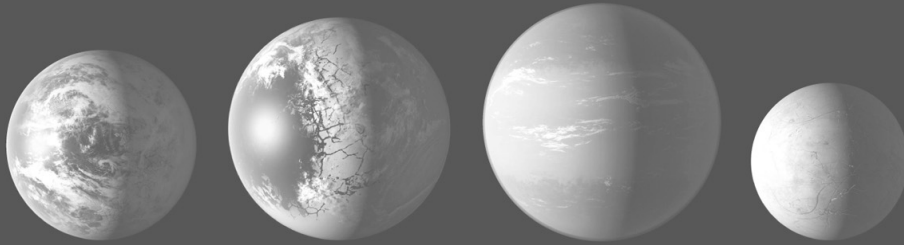
could have liquid water on their surfaces, given the right atmosphere. TRAPPIST-1 will shine for over a trillion years.

Beyond a few trillion years, the last of the red dwarfs will be fading into darkness. Any advanced civilisations still present in the Universe will collect the last rays of the suns by building Dyson spheres; mega structures surrounding the stellar embers to collect every last photon of life-sustaining energy.

In 10 trillion years, all nuclear fusion inside stars will have ceased, and the Universe will be populated by fading white dwarfs, neutron stars and black holes. Our descendants, isolated forever on an island adrift in an ocean of dark, will watch as the galaxy itself evaporates away. In a thousand trillion years, a large fraction of the stellar remnants will have been thrown out of the galaxy due to occasional close gravitational encounters, and the rest will have been swallowed by the super-massive black hole at the galactic centre. The Universe will become a diffuse gas of black holes and inert stellar remnants.

Trappist-1 system			
	B	C	D
orbital period <i>days</i>	1.51 <i>days</i>	2.24 <i>days</i>	4.05 <i>days</i>
distance to star <i>Astronomical Units</i>	0.011 <i>AU</i>	0.015 <i>AU</i>	0.021 <i>AU</i>
planet Radius <i>relative to planet</i>	1.09 R_{earth}	1.06 R_{earth}	0.77 R_{earth}
planet Mass <i>relative to Earth</i>	0.85 M_{earth}	1.38 M_{earth}	0.41 M_{earth}

Solar system <i>rocky planets</i>			
	MERCURY	VENUS	EARTH
orbital period <i>days</i>	87.97 <i>days</i>	224.70 <i>days</i>	365.26 <i>days</i>
distance to star <i>Astronomical Units</i>	0.387 <i>AU</i>	0.723 <i>AU</i>	1.000 <i>AU</i>
planet Radius <i>relative to planet</i>	0.38 R_{earth}	0.95 R_{earth}	1.00 R_{earth}
planet Mass <i>relative to Earth</i>	0.06 M_{earth}	0.82 M_{earth}	1.00 M_{earth}



E

6.10 *days*

0.028 *AU*

0.92 R_{earth}

0.62 M_{earth}

F

9.21 *days*

0.037 *AU*

1.04 R_{earth}

0.68 M_{earth}

G

12.35 *days*

0.045 *AU*

1.13 R_{earth}

1.34 M_{earth}

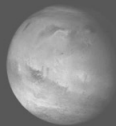
H

~20 *days*

~0.06 *AU*

0.76 R_{earth}

– M_{earth}



MARS

686.98 *days*

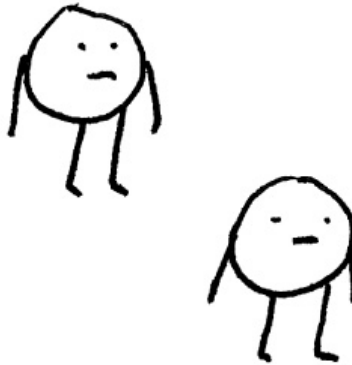
1.524 *AU*

0.53 R_{earth}

0.11 M_{earth}

The TRAPPIST-1 System. Seven rocky planets in orbit around a red dwarf star that will continue to shine for 10 trillion years. Perhaps this will be a home for our decedents in the far future, long after our own sun has died.

The TRAPPIST-1 System. Seven rocky planets in orbit around a red dwarf star that will continue to shine for 10 trillion years. Perhaps this will be a home for our decedents in the far future, long after our own sun has died.



On timescales of a few trillion trillion trillion years, matter itself is thought to be unstable. Protons are stable particles in the Standard Model of particle physics, but many extensions to the Standard Model, known as Grand Unified Theories (GUTs), predict that protons (and neutrons bound up inside neutron stars) will decay with half-lives in the region of 10^{34} years. Just like the radioactive decay of atomic nuclei, proton decay is a statistical process, and we can therefore do experiments to search for it by observing a very large number of protons. The Super-Kamiokande detector in Japan, which also detects neutrinos from the Sun and supernova explosions, is used to search for proton decay. The experiment has seen no signal to date, but this allows us to place a (model dependent) lower limit of around 10^{34} years on the proton lifetime. Such experiments are able to test many of the most popular GUTs, and with future planned upgrades it is possible that proton decay will be observed, allowing us to predict precisely when all the white dwarfs and neutron stars in the Universe will have evaporated.



Protons would decay into positrons (anti-matter electrons) and particles called pions, which immediately decay into two photons. As far as we know, electrons, positrons, photons and neutrinos are stable particles, and

the Universe would be populated by black holes adrift in a sea of electrons, positrons, neutrinos and photons.

It seems unlikely that life could persist in a universe in which the last stellar remnants had faded or decayed away.

Perhaps there is some way by which the intense gravitational fields around black holes could be harnessed to provide the energy for information processing to continue beyond a trillion trillion trillion years, but even this source of energy will not be eternal because black holes also have a finite lifetime.

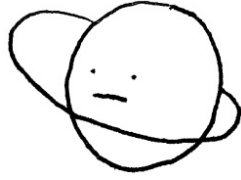


Black holes have a temperature; they glow very faintly through a process known as Hawking radiation. The temperature of a black hole is inversely proportional to its mass, so as a black hole loses mass by emitting Hawking radiation, somewhat paradoxically it heats up and radiates more strongly. Eventually this runaway process results in the explosion of the black hole in a flash of high-energy gamma radiation, and all the mass is returned to the Universe.

The process is extremely slow for stellar mass black holes, and much longer for the super-massive black holes at the hearts of galaxies. A black hole the mass of our sun has a temperature of 60-billionths of a degree above absolute zero, which means that it will currently absorb energy from the much-hotter cosmic microwave background radiation (CMB), which is at a temperature of 2.7 degrees. In the very far future, however, the CMB will have cooled due to the expansion of space, and even the most massive black holes will evaporate away. A solar mass black hole is predicted to have a lifetime of around 10^{67} years, and the super-massive black holes may live for 10^{100} years.⁴



Beyond 10^{100} years, there will be nothing but darkness. The Universe will be an ever-diluting sea of the lightest subatomic particles, separated by such vast distances that they will never interact. There will be no temperature differences, no structures, and it will not be possible for a single bit of information to be stored. The bright young history of the Universe – the planets and moons and mountains and rivers and seas and stars, everything that ever was – will be forgotten; erased, as if it never existed. Time will have no meaning because nothing will happen. This is known as the heat death of the Universe, and it will be forever.



Beyond a few trillion years, any advanced civilisations still present will collect the last rays of the suns by building Dyson spheres.



A Dyson sphere. In the far future, advanced civilisations may completely surround fading stars in order to utilise every last photon of starlight in the Universe.

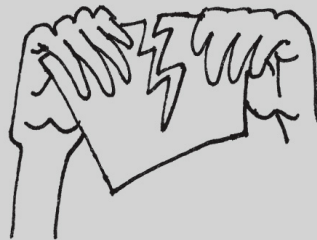


10^{100} years is a long time. If you started counting the years with atoms, you'd use all the atoms in the observable Universe to get to 10^{80} , which isn't even close. You'd need a hundred million million million universes' worth of atoms to reach your goal. So we needn't worry too much – perhaps we should focus on making it through to the end of the Trump Presidency and take it from there.

Something remains in the darkness, though. An idea. Our time is temporary. We know this as individuals. A century at most. We will leave a legacy if we're lucky. Children, works, memories. We all leave an imprint on the future in myriad tangled ways. But ultimately nothing will survive. It will all be gone. How does that make you feel? This is not a trivial question; it goes to the heart of the human condition. The world's great religions, the pyramids, cathedrals, Shakespeare, Mahler, Plath, Kubrick, Austen, Van Gogh, Lynch. Art, philosophy, literature, music; these are responses to the finite nature of individual existence; the great existential challenge often resolved by taking refuge in the immortality of culture or soul. Science tells us this is a false resolution. There is no immortality, the laws of nature forbid it. Meaning is temporary, because it is contingent on the existence of material structures and the flow of energy, and these resources are not eternal in our expanding universe. Cosmology is the ultimate exercise of reason, and our reason confirms what we have always known, deep down. Whether human or star, life is short, precious and fleeting. The Universe will spend an eternity in darkness after a brief period of light, and we are most fortunate to have had the opportunity to discover this deep truth. This is the meaning of life, or at least the only idea that we might call meaning. We must understand that existence is finite; perhaps in doing so we will

come to recognise the true value of ourselves, our fellow humans and our civilisation.

**We are nothing but monkeys;
residents for the briefest of time in
an infinite cage. But what
magnificent monkeys we are.**



Alternate futures

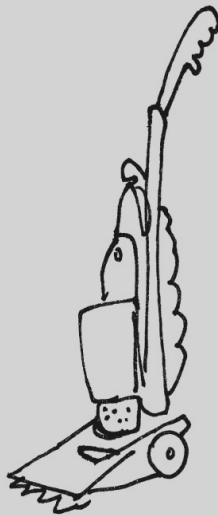
A future of exponential expansion is the most likely fate of the Universe given our current theoretical understanding and our measurements of the contents of the Universe, but there are other possibilities.

THE BIG RIP

The Big Rip may be the most human of ends as it delivers needless violence and hectic spectacle. Rather than gravity being victorious, gravity loses control. Galaxies will be torn asunder and molecules and atoms will be shredded. This is the end of the Universe as directed by Michael Bay.

As far as we can tell at present, dark energy takes the form of a cosmological constant in Einstein's equations, which means that it stays perfectly constant per unit volume of space as the Universe expands. This is what leads to the exponential expansion of the Universe in the far future, and the 20 billion years or so doubling time we quoted in the main text. There are theories, however, in which the dark energy density can grow as the Universe expands, and the expansion rate of the Universe increases without bound. In such scenarios, all galaxies, stars, planets and even atoms and atom nuclei are ultimately ripped apart by the expansion of space in what is known as the Big Rip. If dark energy behaves in this way, our future demise will be a lot sooner than the ambling heat death we described here. Some estimates suggest the Big Rip could happen in only 20 billion years, well within the possible lifetime of intelligent civilisations.

AN UNSTABLE UNIVERSE



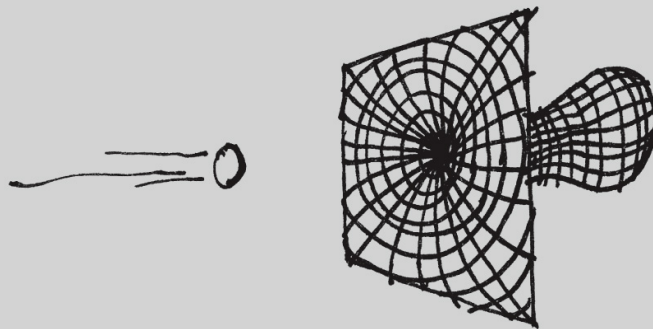
It is also possible that our universe itself is not stable. The Universe could be in what physicists call a 'false vacuum' state. You can picture the vacuum as a series of valleys in a landscape. Physics as we know it today takes place in one of the valleys (known as the electroweak vacuum), but if there is a lower valley somewhere, it is inevitable that the Universe will shift into it eventually. This would amount to a complete reconfiguration of the masses of the particles and the forces

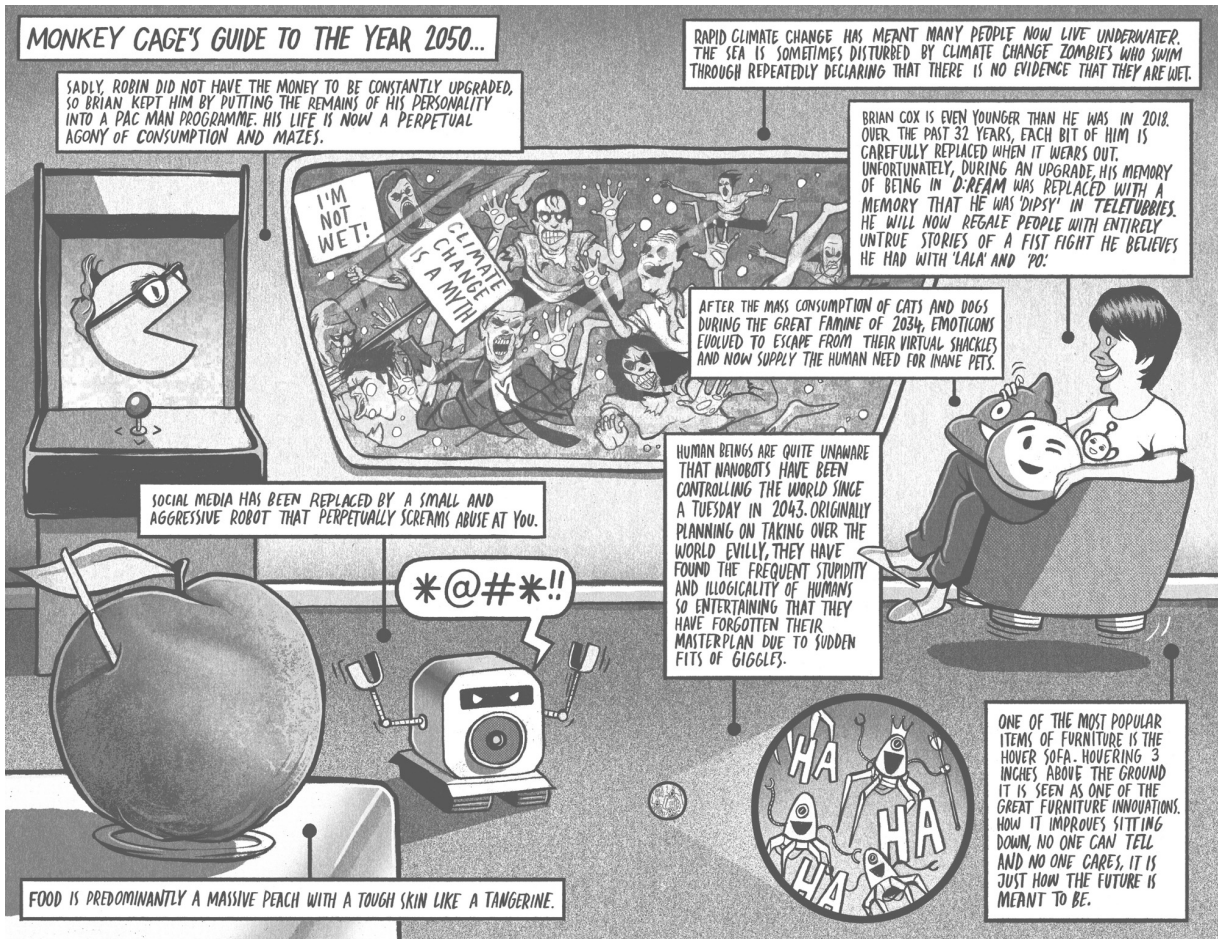
between them. The Universe in the lower valley would be a very different place, and may not support the existence of stars and planets and galaxies and life. In the Standard Model, the shape of the landscape is determined by the Higgs potential, which depends most strongly on the masses of the Higgs boson and the Top quark.⁵ Intriguingly, the measured mass of the Higgs boson at the Large Hadron Collider of 125 GeV and the Top quark mass of 172 GeV appears to place our universe in a ‘meta-stable’ region between stability and instability.⁶ If indeed our universe is in a false vacuum state, the Universe as we know it has a finite lifetime; at some point it will transition into the true vacuum. Intriguingly, the problem of the stability of the electroweak vacuum is more acute during inflation, because fluctuations in the Higgs field are intensified, and there is a great deal of theoretical work at present in searching for potentially new physics that could be responsible for stabilising the electroweak vacuum. So, is the Universe stable? The answer is, we don’t know!



THE BIG CRUNCH

A third possibility is the Big Crunch; the Universe may ultimately re-collapse. If you have ever been struck in the eye by a maximum stretch rubber band pinging back, imagine the pain of being struck in the face by a universe pinging back to its Planck time days. There are models in which dark energy changes over time. If the dark energy density increases, we get the Big Rip discussed above. But other models suggest that dark energy might behave more like the inflaton field which drove cosmic inflation before the Hot Big Bang. We know that inflation stopped, at least in our region of the Universe, and that this resulted in the transformation of the inflaton field into the matter and dark matter that makes up our universe today. Could dark energy be a field like the inflaton field, and could the same happen, causing the expansion of the Universe to go into reverse? The answer is yes, and calculations suggest that the Universe would re-collapse very rapidly after the dark energy field decayed. Current theoretical estimates suggest a 'cosmic doomsday' date in these scenarios of no less than 24 billion years, but no later than around 3650 billion years. The paper from which these figures were taken (Wang et al., JCAP 0412:006, 2004) contains a magnificent sentence which illustrates the difference between scientific doomsday predictions and the more familiar drivel with which anyone who spends time on social media will be familiar. 'This doomsday prediction is model dependent.'





Thank you for reading
The Infinite Monkey Cage book
 in whichever Universe you are in.
 We hope you are enjoying the reality
 that you seem to be experiencing.

**Please remember that your
 experience of this book was
 subjective and you have greatly
 contributed to any joy or
 disappointment that you have**

**appeared to feel during the reading
of it.**

Here is your homework.

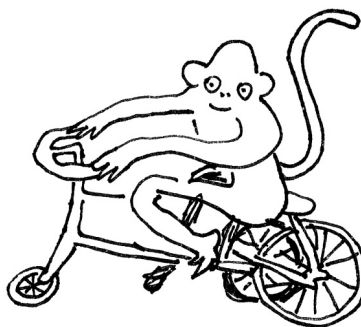


Your challenges:

1. Explain in one hundred words why you are not living in a simulation. Some of you may find this easier than others as Brian oversaw the simulation of half of the readership and Robin

simulated the other half. See if you can work out who your simulator was.

2. Come up with as many replies in sixty seconds for ‘if we come from monkeys, how come there are still monkeys?’ For example: ‘Because something has to ride the tricycles in an Eastern European zoo’.
3. Who said, ‘the sight of the feathers in a peacock’s tail makes me sick’?
4. Using three pebbles and a piece of string, derive Pi to 217 decimal places.
5. Using soot, lard, a jam jar and fork lightning, create life.
6. Name three different methods for resuscitating a dead strawberry.
7. Show that it is possible to build a Universal Turing machine out of Lego. Hence, or otherwise, create Robin. You may omit the cardigan.



¹ Assuming dark energy is the cosmological constant.

² We can calculate the Hubble Constant in the far future from the Friedmann Equation, given that we know the amount of dark energy in the Universe and the Hubble Constant today. In the far future,

$H(\infty) = H_0 \sqrt{\Omega_{\Lambda,0}} = H_0 \sqrt{0.7} = 56 \text{ km/s/Mpc}$ tells us that the Universe will double in size every 20 billion years.

³ To be precise, two electrons cannot occupy the same quantum state.

⁴ If there are very light black holes in the Universe, perhaps produced at the end of Inflation in the extreme conditions of the Hot Big Bang, their lifetimes would be of the order of the current age of the Universe and their explosive decay should be observable. NASA's Fermi Gamma-ray Space Telescope is currently searching for decaying primordial black holes, but no signals have been confirmed to date. A black hole of mass 10^{11} kg would have a lifetime approximately equal to the current age of the Universe.

⁵ During proofreading, the ever-diligent Prof Jeff Forshaw noted that we should insert the Higgs Self-coupling into this list.

⁶ See, for example, Degraasi et al. JHEP08(2012)098.

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Brian Cox, Robin Ince and Sasha Feachem
September 2017

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About the Book

The legendary BBC Radio 4 programme brings you this irreverent celebration of scientific marvels. Join us on a hectic leap through the grand and bizarre ideas conjured up by human imagination, from dark matter to consciousness via neutrinos and earthworms.

About the Authors

Professor Brian Cox, OBE FRS is Professor of Particle Physics at the University of Manchester and the Royal Society Professor for Public Engagement in Science. He is best known as a science broadcaster and presenter of the popular BBC *Wonders* trilogy, *Human Universe*, *Forces of Nature* and *Stargazing Live*, as well as co-presenting BBC Radio 4's multi-award winning science/comedy show *The Infinite Monkey Cage*. He was also the keyboard player in the UK pop band D:Ream in the 1990s and used to be a bus spotter.

Robin Ince was in a far less successful band than Brian Cox called The Reg Gutteridge Experience. Their songs have not been used by any political party as an anthem, not even 'The Hornsey Axe Murderer'. As well as shows about science he does podcasts about angry music with Michael Legge (*Vitriola*) and *The Book Shambles Podcast* with Josie Long. He has sometimes received awards for his stand-up which is about stuffed goats in galleries and Kurt Vonnegut. He lost a round of *Just a Minute* after saying 'allo allo' when his brain needed a reference to a sitcom. Paul Merton was gleeful. He has also edited two anthologies of horror stories by comedians called *Dead Funny*. He is best known for presenting *The Infinite Monkey Cage* with Brian Cox on BBC Radio 4.

Alexandra (Sasha) Feachem is the producer and co-creator of BBC Radio 4's multi-award winning science/comedy show *The Infinite Monkey Cage*. When she is not trying to contain the monkeys inside their infinite cage, she can be found in the less roomy environment of the BBC Radio Science Unit making all manner of science shows and documentaries for BBC Radio 4 and the BBC World Service.

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